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**DESIGN, IMPLEMENTATION, AND INVESTIGATION OF AN  
IMAGE GUIDE-BASED OPTICAL FLIP-FLOP ARRAY**

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## LIST OF ABBREVIATIONS

LCLV	Hughes liquid crystal light valve
LCLVi	Input plane of the light valve
LCLVo	Output plane of the light valve
IGi	Input plane of the image guide
IGo	Output plane of the image guide
Ln	Lens n
Mn	Mirror n
BSn	Beamsplitter n
SW	Space-bandwidth product
IIP <sub>LV</sub>	Intermediate Image Plane containing the image of the light valve output
IIP <sub>IG</sub>	Intermediate Image Plane containing the image of the image guide output
IIP <sub>0</sub>	Intermediate image plane containing the system output
VIP <sub>LV</sub>	Virtual image plane, serves as the object for IIP <sub>LV</sub>

## CHAPTER I

### INTRODUCTION

#### A. OVERVIEW

This report presents the design for an image guide-based optical flip-flop array created using a Hughes liquid crystal light valve and a flexible image guide in a feedback loop. This design is used to investigate the application of image guides as a communication mechanism in numerical optical computing.

A simplified drawing of the design for this image guide-based optical flip-flop array is shown in Figure 1. The output of the light valve is imaged onto the input of the image guide and the output of the image guide is imaged onto the input of the light valve, creating a feedback loop. The light valve is being used as a nonlinear amplifier. Due to the nonlinear nature of the light valve's amplification it is possible to create an intensity bistable device in this configuration (in a manner identical to that in which feedback in nonlinear transistors is used to form electronic flip-flops). The image guide serves to spatially quantify the feedback light into a distinct array corresponding to the array formed by its fibers. Thus, it creates an array of independent optical flip-flops, each of which consists of one fiber from the image guide, the corresponding area of the light valve, and the feedback loop.



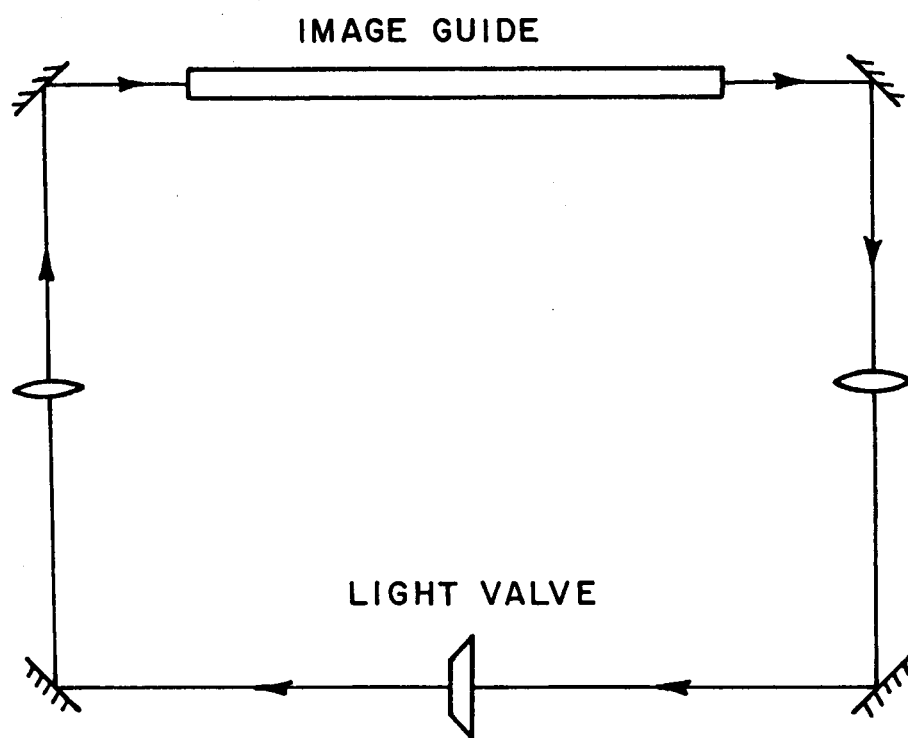


Fig. 1: Simplified sketch of the image guide-based optical flip-flop array.

An optical flip-flop array utilizing the light valve has previously been constructed [1]. In this report, however, the theory behind that original design has been taken and implemented again with the addition of an image guide in the feedback loop. Thus, in addition to demonstrating the ability to recreate the original results based only upon a sketch of the apparatus and the theory, work is carried out in investigating the usage of an image guide in such a system, which has not been previously done. Furthermore, the original design proved inadequate for alignment purposes due to the presence of the image guide. An alignment procedure was developed which would enable easy and accurate alignment of the system even with the image guide present. This procedure also proved useful in analyzing the image guide.

There are four aspects of this device which will be addressed in this report. First is the theory upon which the operation of this device is based. Second is the procedure developed to easily and accurately achieve one-to-one imaging around the feedback loop, which is required for operating the system. Third is the conditions and results under which this device was tested. Fourth is an analysis of the image guide to determine its desirable characteristics and inherent problems when used in this manner in an optical system.

## B. BACKGROUND

The design for this device draws upon the areas of feedback (both electrical and optical), optical computing, and fiber optics. Some of the relevant background is given below.

Feedback is an integral part of control theory and is used extensively in electronic design in one form or another. For example, operational amplifiers are used with feedback to produce amplifiers, integrators, and oscillators. Automatic gain control (AGC) circuits are another widely used form of feedback. In digital electronics, feedback is used to create flip-flops, which are very useful bistable devices.

But feedback is also used in optical systems. A hybrid Fabry-Perot resonator with electrical feedback has been built and shown to be able to be used in many ways, such as optical memory, differential amplifier, logic element, and an analogue-to-digital converter [2]. A feedback system composed of a TV camera and monitor has been demonstrated to have similar applications [3]. Optical systems with optical feedback have been created as well. Flip-flops [4], logic gates [5], and a bistable matrix [1] have all been implemented in this manner using the light valve.

Optical computing is an area in which a lot of work is currently occurring [6]. There are several potential advantages which optical computers have over electronic computers. Among these are a high degree of parallelism, reconfigurability, and interconnection capability. At one time efforts were concentrated upon creating the optical analogues of the basic building blocks of electronic computers (logic gates, flip-flops, etc.). Now efforts are in the areas of multiple-valued processing, interconnects, and general architectures.

An image guide has the potential to be a two dimensional data bus between the components of an optical computer, since it can be thought of as a matrix of independent optical channels. It can easily pass

images from one place to another, eliminating the need for complicated optical systems. Furthermore, it can bend around corners and be made any reasonable length with the same technology. Work has been done to characterize the transmission quality of image guides [7] but there is more work to be done on their use.

Image guides have existed since before 1959 [8,9]. They are currently being used, as the name suggests, to transmit images from regions which are not easily observed. For example, the medical profession uses them to examine the inside of the human body [10,11]. They are also used extensively to examine the inside of machinery, such as airplane engines, without having to dismantle them. But this thesis appears to be the first time an image guide has been used as an array of independent optical data channels instead of simply as an imaging system.

The technology to make and utilize optical fibers is well developed because of the widespread use of fibers for long distance communication. Fibers are attractive for communication purposes because of their light weight, small size, and high bandwidth. There are plans for an intra-state fiber optic network for the state of Florida [12] as well as an undersea cable in the Pacific [13]. Because of the work already done with fibers, it should be relatively easy to adapt them for communication between and inside optical computers.

The problem addressed here is to create an image guide-based optical flip-flop array using a liquid crystal light valve and an image guide in a feedback loop, and to analyze the useful characteristics and inherent problems associated with the image guide for such optical

computing applications. As part of the solution to this problem, an alignment procedure is to be developed in order to enable the system to be aligned even with the presence of the image guide.

#### C. CHAPTER CONTENTS

The remainder of this report is devoted to explaining the various aspects of the design and operation of this image guide-based optical flip-flop array and presenting the results and conclusions based upon its operation. This report is organized in the following manner.

There are five chapters. The remaining four include the following information. Chapter II contains the theory behind the operation of this device. Chapter III contains a description of the apparatus and its operation. In Chapter IV the conditions under which this system was tested are presented along with the results achieved. In addition, the advantages and disadvantages of characteristics of the image guide are discussed in light of the results observed by its use in this system. Finally, Chapter V contains a summary of the results and the conclusions drawn in this report as well as suggestions for further areas of research.

## CHAPTER II

### THEORY

#### A. INTRODUCTION

This chapter contains the theories upon which the image guide-based optical flip-flop array is based. These theories are presented here so that they can be referred to later in this report when they are needed.

These theories fall into six categories. One section has been devoted to each. First is the operation of the liquid crystal light valve (henceforth abbreviated LCLV) and its response in the feedback configuration shown in Figure 2 (Section B). Second is the theory of image guide operation (Section C). Third is the theory of imaging using lenses and how small perturbations affect magnification (Section D). Fourth is the theory of space-bandwidth product in optical systems (Section E). Fifth is the resolution of two imaging systems: a lens and the light valve (section F). Finally, a set of criteria sufficient for the existence of an optical flip-flop array will be presented and discussed.

#### B. LIGHT VALVE

In this section the operation of the light valve will be discussed. Then it will be shown that, under feedback, there exist at least one and usually two stable intensities. This fact will be useful, because the existence of two stable intensities is the heart of an optical flip-

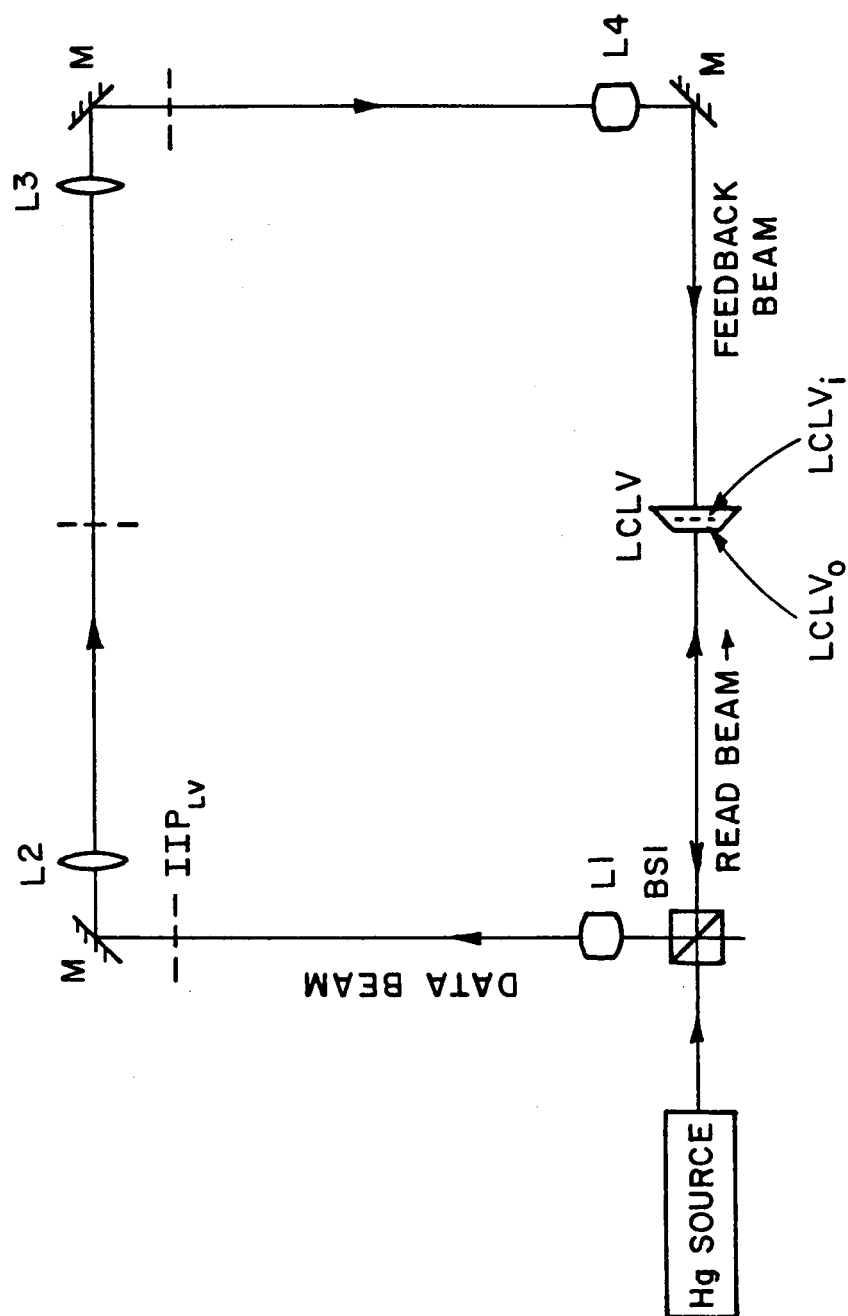


Fig. 2: Sketch of feedback loop involving the LCLV.

flop. A Hughes liquid crystal light valve constructed in the parallel (untwisted) nematic alignment is used. The analysis will be conducted for a single point on the light valve. It will be assumed that the feedback is spatially one-to-one.

The light valve can be viewed as an optically controlled, birefringent mirror [14]. The birefringence of the light valve output is controlled by the intensity of the input light via the photoconductor upon which it impinges. A voltage is placed across the serial combination of the liquid crystals and the photoconductor, which determines the input/output operating curve of the light valve. As the input intensity increases, the conductivity of the photoconductor increases, thus increasing the electric field across the liquid crystals, which increases their tilt, thus changing the birefringence of the light valve output. In this manner the input voltage controls the birefringence of the output.

Because the birefringence of the output of the light valve can be controlled by the input light, it is possible to create an optical amplifier if two crossed polarizers are combined with the LCLV in the following manner. The first polarizer is used to linearly polarize a beam of light (which shall be referred to as the Read beam because it 'reads' the state of the LCLV). This Read beam is reflected off of the output plane of the LCLV and passed through the second (crossed) polarizer. Designate the light which passes through the second polarizer as the Data beam, because this will contain the information imparted by the LCLV.



The intensity of the Data beam is a function of the intensity of light present at the light valve input. This can be seen by analyzing the effect the LCLV has upon the Read beam. Because of the birefringent nature of the light valve output, it possesses a fast and a slow axis. This will introduce a phase shift between these two components of the linearly polarized Read beam (provided the axis of polarization does not align with one of the axes of the light valve). This phase shift becomes apparent when the Read beam passes through the second polarizer. The intensity of the light which passes through the second polarizer is directly dependent upon the phase shift introduced. If no phase shift is introduced, no light will pass through. If there is a  $90^\circ$  phase shift introduced by the light valve then all of the light in the Read beam will pass through the second polarizer. The phase shift is a function of the tilt of the liquid crystals which is controlled by the intensity of light present at the light valve input. Therefore, this light controls the intensity of the Data beam.

This control of the Data beam intensity by the light present at LCLVi can result in optical amplification. The intensity of the light at LCLVi determines what percentage of the Read beam intensity is present in the Data beam. But in none of this discussion was the intensity of the Read beam mentioned. Therefore, it is possible to make the intensity of the Read beam much greater than the intensity of the light at LCLVi. This results in a weak input to the system (the light at LCLVi) controlling a strong output (the Data beam). Functionally, this is the optical equivalent of a transistor. Transistors used as amplifiers are nothing new.

The LCLV can be used as a nonlinear amplifier, so the possibility exists for stable intensities under optical feedback. This feedback is shown in Figure 2. The light valve is being operated as an optical amplifier with the input labelled the Feedback beam and the output labelled the Data beam. The roles of the crossed polarizers for the amplifier are performed by a Glan-Thompson beamsplitter cube (BS1). Lens L1 images LCLVo onto the plane designated IIP<sub>LV</sub>. But the only light passing through L1 is the Data beam, whose intensity is a function of the image at LCLVi, hence the image at IIP<sub>LV</sub> is a function of the image at LCLVi which means this part of the system is acting as an image amplifier. The image at IIP<sub>LV</sub> is imaged back onto LCLVi via lenses L2, L3, and L4, thus providing the optical feedback.

Gerlach, et. al. [1] performed an analysis of the LCLV response under such feedback for a single point and proved the ability to achieve at least one and usually two stable states. The remainder of this section is a brief summary of their results as they apply to this design.

In order to easily analyze the response under feedback, we shall model the light valve response and the feedback as a series of equations. Define  $I_1$  as the intensity of the Data beam in IIP<sub>LV</sub>. Define  $I_2$  as the intensity of the Feedback beam at LCLVi. Let  $B(I_2)$  be the function relating the phase delay between the fast and slow axes of the LCLV to the input intensity  $I_2$ . This phase delay is a function of the tip of the liquid crystals which is controlled by the intensity of light at LCLVi. With these definitions we model the response of the light valve at a given point as

$$I_1 = c + b \cdot \sin^2(B(I_2) + u) \quad (1)$$

for constants  $b$ ,  $c$ , and  $u$  which are determined by the physical configuration of the system, the intensity of the read beam and the LCLV voltage. Furthermore, in the region in which the stable states lie,

$$B(I_2) = kI_2 \quad (2)$$

for a positive constant  $k$ . Substituting equation (2) into equation (1) yields

$$I_2 = c + b \cdot \sin^2(kI_2 + u) = F_1(I_2) \quad (3)$$

where  $F_1(I_2)$  is used to designate the response of the light valve.

Because we are assuming that the optical feedback is spatially one-to-one, we can model the feedback at any point by the load-line

$$I_2 = \alpha I_1 = F_2(I_1) \quad (4)$$

where  $\alpha$  characterizes the attenuation around the loop and  $F_2(I_1)$  is used to designate the response of the feedback loop.

A simultaneous solution of equations (3) and (4) gives the equilibrium points for this system. These equilibrium points are the intersections of the two curves when they plotted on the same graph. This is done in Figure 3. It can be seen that there are three equilibrium points.

The stability criterion for equilibrium points found through this method is based upon the slopes of the curves involved. If the product of the slopes of the two curves is less than unity then the equilibrium point is stable. This is represented mathematically as

$$F_1' F_2' < 1 \quad \text{stable equilibrium} \quad (5)$$

$$F_1' F_2' > 1 \quad \text{unstable equilibrium} \quad (6)$$

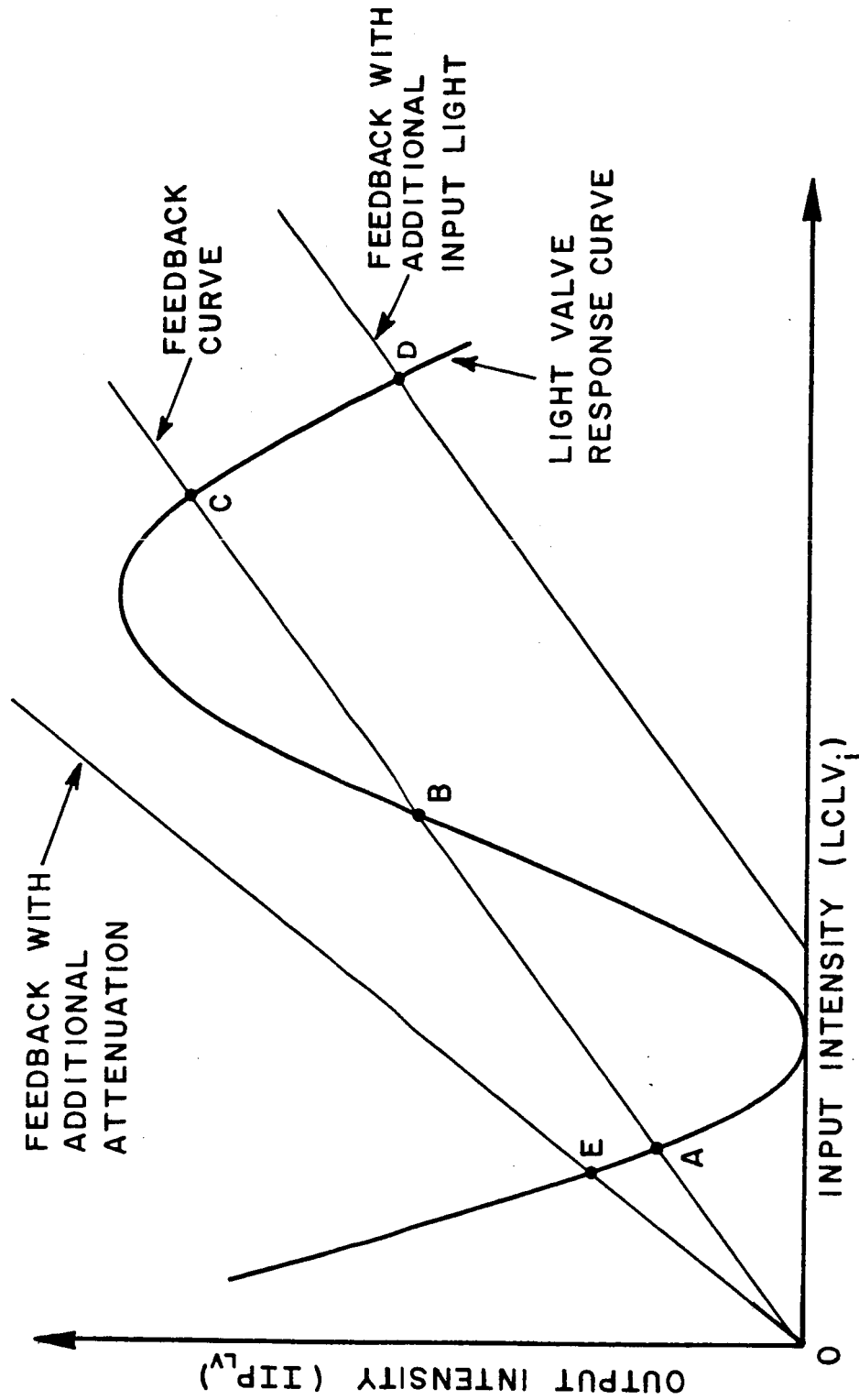


Fig. 3: Plot showing the operating characteristics of the LCLV under feedback. Points A, C, D, and E are stable operating points, whereas B is an unstable operating point.

Using this criterion, it is obvious that points A and C are stable equilibrium points and point B is an unstable equilibrium point. This means that there are indeed two stable intensities under feedback. Henceforth these will be referred to as the dim and bright states. (Notice that if the load line were not as steep, it would be possible to have more than two stable states.)

It is possible to change from one stable state to another by adjusting the intensity of the light at the LCLV input. This can be seen by examining the change in the feedback curve in Figure 3 when light is added or subtracted from the light valve input. If an external light source is used to increase the light incident upon LCLVi then the new feedback curve will be parallel to but below the old feedback curve (as shown in Figure 3). For a sufficient increase in the light, the stable equilibrium point A will no longer exist and the system will settle at state D. When the extra light is removed the system will decay to state C. Hence, the system has been changed from the dim state to the bright state by this procedure. On the other hand, if the attenuation of the feedback beam is increased then the slope of the feedback curve will increase (which is also shown in Figure 3). For a sufficient attenuation the stable state C will cease to exist and the system will settle into state E. When the added attenuation is removed the system will decay to state A. Thus, the system has been changed from the bright stable state to the dim stable state by this procedure.

In summary, the operation of the light valve as an image amplifier has been explained and the potential existence of two stable states

under feedback has been derived. In addition, we have seen how to change from one stable state to the other.

### C. IMAGE GUIDE

In this section the theory of image guide operation will be briefly discussed. Attention will be given to those aspects which will be needed to understand the operation of the optical flip-flop array.

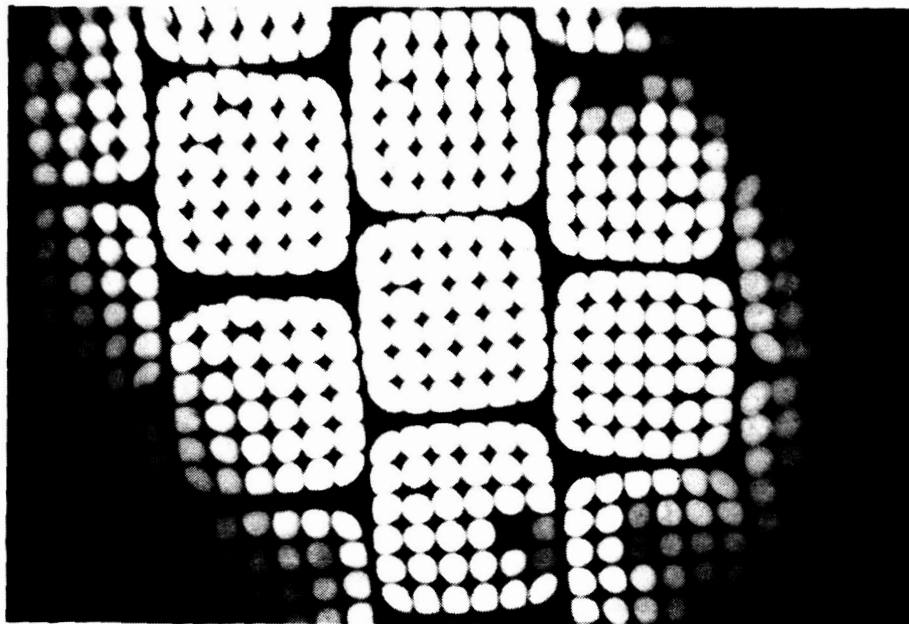
An image guide is an ordered collection of optical fibers which are arranged so that the spatial relationship between them is the same at both the input and output of the image guide. Therefore, a pattern illuminating the fibers at the input will correspond one-to-one with the pattern formed by the fibers at the output (discounting the minor distortions introduced by the image guide).

A picture of the output end of an image guide is shown in Plate I. Each spot corresponds to the core of one fiber. The space between these fibers is the cladding. It can be seen that the fibers are grouped into six by six arrays. These are referred to as fiber bundles. The fibers form very regular arrays within the bundles but the bundles do not form a regular array. This is due to the manufacturing process. A shift in the relative positions of the bundles between the input and the output will result in a distortion of the transmitted image.

To understand how the image guide operates, one must first understand how an optical fiber transmits light. An optical fiber is merely a dielectric waveguide operating at optical frequencies. It can be analyzed in depth using electromagnetic theory [15]. The details of this will not be given here because they are not necessary to understand

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Plate I: Photograph of the output face of the image guide used  
in this report.



the operation of the flip-flop array. It is sufficient to understand that an optical fiber guides light from one end to the other by a series of reflections off of the wall of the fiber. The light reflects due to total internal reflection (which is a function of the angle of the light and the indices of refraction of the core and the cladding).

In general terms, an optical fiber has an acceptance cone. This is related to the angle at which total internal reflection will occur within a fiber. Light incident upon the fiber at an angle within this acceptance cone will be trapped by the fiber and propagate to the other end. Light which is incident at an angle larger than the acceptance cone will not be trapped and hence won't propagate. Due to the nature of the propagation, however, the intensity distribution at the input of the fiber is not conserved. The output intensity distribution is a function of the modes of propagation. For our purposes we shall consider it as essentially a uniform average of the intensities present at the input of the fiber.

The way in which an image guide transmits an image can be understood quite easily by comparing it to a black and white television picture. The original scene from which a television picture is made is continuously distributed both spatially and in intensity, just like the image at the input of an image guide. But when a television picture recreates the image, it does so by using a pattern of dots, each of which is of uniform intensity. The intensity of a single dot is the average of the intensities of the original picture in the corresponding location. These dots form a picture to our eyes because they are sufficiently close together that the space between them is less than the



point response function of our eyes (i.e. the spatial bandwidth required to resolve the space between the dots is much higher than the bandwidth response of our eyes). Hence, the individual dots blur into a continuous distribution and the result looks like the original picture. An image guide recreates an image in the same manner except that the dots are the outputs of individual fibers. An image guide used in this manner will be referred to as an image conduit in this report.

But an image guide need not transmit just images. It can carry position coded data by letting each fiber carry one bit of data (instead of one pixel of an image). In this manner it can be used as an optical data channel array for communicating between optical components. Individual fibers are currently used as single channels in telecommunications but an image guide has the advantage of possessing a large number of fibers in a compact area.

The difference between an image conduit and a data channel array can be seen by comparing the future imaging of their outputs. The outputs of the individual fibers of an image conduit are not important, only their overall intensity distribution. Therefore, future imaging systems do not need to resolve the individual fibers in future imaging systems. This is not the case with a data channel array. Future imaging systems must resolve the individual fibers because the outputs of the individual fibers must remain independent.

Image guides can be made either rigid or flexible. Flexible image guides, like flexible fibers, can be easily bent to transmit light around corners. Also, the distance and orientation between object and image can be changed simply by moving the two ends of the image guide. This is a big advantage over lens systems for transmitting images.

The image guide in this flip-flop array is used both as a spatial quantifier and as an optical matrix bus. It defines the array in which the flip-flops are positioned via the array in which its fibers are positioned. It is also used to convey this array part of the way around the feedback loop. The ability to adjust the orientation between input and output was used to advantage as will be seen later.

#### D. LENS SYSTEMS

In this section the imaging relationships for lenses will be used to analyze the effect of small perturbations in the object and image distances upon the magnification and lens position when we require that imaging be maintained. The results of this analysis will be useful when aligning the system. They will tell us how far to move the object and image from their present position in order to achieve the desired change in magnification and how much to move the lens in order to maintain imaging.

The analysis will be carried out in several stages. First the original system -- consisting of a simple lens, an object and its image -- will be characterized and the relevant equations given. Then the perturbed system will be similarly characterized and the relationships between these two systems will be given. Based upon these relationships the information of interest will be derived.

The system being analyzed is shown in Figure 4. The system consists of a single lens, an object, and its image. The solid lines represent the unperturbed system. The perturbation consists of moving

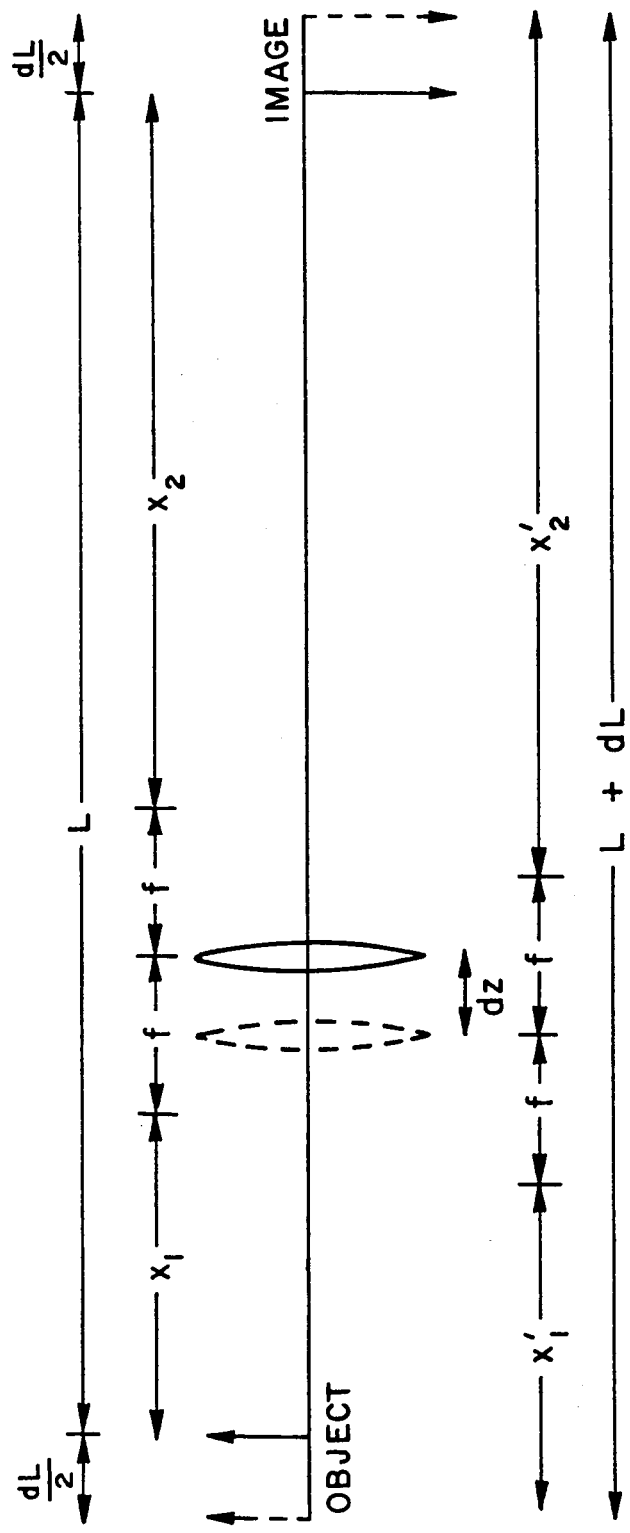


Fig. 4: Sketch showing the changes in a lens system under a perturbation. Solid lines represent the unperturbed system. Dashed lines represent the perturbed system.

the object and image planes an equal distance ( $dL/2$ ) away from the lens. We are interested in the new position of the lens so that it will image the object plane onto the image plane and the change in magnification which results. This situation is represented by the dashed lines in Figure 4.

For the quantities of interest in the unperturbed system the following notation will be used:

$f$  = focal length of the lens

$x_1$  = distance from object to focal point of lens

$x_2$  = distance from focal point to image

$L$  = path length from object to image

$m$  = magnification

From these definitions it can be seen that

$$x_1 + x_2 = L - 2f \quad (7)$$

We shall assume that the object is closer to the lens than the image, which is expressed

$$x_2 > x_1 \quad (8)$$

The Newtonian thin lens equation gives us the following results:

$$x_1 x_2 = f^2 \quad (9)$$

$$m = x_2 / f \quad (10)$$

$$L > 4f \quad (11)$$

Using equations (7), (8), and (9) we can algebraically derive

$$x_2 = (L - 2f + \sqrt{L(L - 4f)}) / 2 \quad (12)$$

We shall perturb this system in a specific manner: the object and the image planes shall both be moved a distance  $dL/2$  away from the lens (as shown in Figure 4); then the lens will be moved to reimage the

object plane onto the image plane. In this perturbed system we shall use the following notation:

$x_1' =$  new object distance

$x_2' =$  new image distance

$m' =$  new magnification

$dL =$  change in path length

$dx_2 =$  change in image distance

$dZ =$  distance which the lens moves toward the object to maintain imaging

$dm =$  change in magnification

Using these definitions and the known imaging relationships we shall derive an expression for  $dZ$  and  $dm$  in terms of  $dL$ . From these definitions the following equations can be written:

$$dx_2 = x_2' - x_2 \quad (13)$$

$$dm = m' - m \quad (14)$$

$$= dx_2 / f \quad (15)$$

$$x_2' + f = dZ + x_2 + dL/2 \quad (16)$$

Substituting equation (13) into (16) and rearranging gives

$$dZ = dx_2 - dL/2 \quad (17)$$

In this analysis the perturbation is small, so we can approximate the change in any parameter, as a function of the change in path length, by taking the derivative with respect to  $L$  and multiplying by  $dL$ . We are specifically interested in  $dm$  and  $dZ$ , both of which depend upon  $dx_2$ , so we shall approximate  $dx_2$  by

$$dX_2 = dL \frac{d}{dL}(X_2) \quad (18)$$

Taking the derivative of both sides of equation (12) and substituting into equation (18) gives

$$dX_2 = dL(1+(L-2f)/\sqrt{L(L-4f)})/2 \quad (19)$$

We are now ready to derive our desired results. Substituting equation (19) into equations (15) and (17) yields

$$dm = dL(1+(L-2f)/\sqrt{L(L-4f)})/(2f) \quad (20)$$

$$dZ = dL(L-2f)/(2\sqrt{L(L-4f)}) \quad (21)$$

which gives us the change in magnification and lens position for the given perturbation. Notice that  $dm$  and  $dZ$  both have the same sign as  $dL$ .

#### E. SPACE-BANDWIDTH PRODUCT

In this section the space-bandwidth product for an optical image will be discussed. The space-bandwidth product (henceforth designated SW) for an optical image in an optical system is analogous to the time-bandwidth product for a signal on a communication channel. Both are means of characterizing the data in a manner that is reasonably invariant under normal transformations that preserve the data. The information in this section is based upon notes of a talk given by A.W. Lohmann [16].

As with every analysis there are certain assumptions made about the system and image involved. For this discussion, it will be assumed that the imaging system in question is spatially bandlimited and has a continuous distribution of possible image points. A lens is an example

of such a system. Furthermore, it will be assumed that the image likewise meets these conditions.

The space-bandwidth product is the product of the space (or area) which an image occupies with the two-dimensional bandwidth in the spatial frequency domain. Assuming both the image field and the spatial frequency domain have a rectangular shape, then

$$SW = \Delta x \Delta y \Delta \kappa_x \Delta \kappa_y \quad (32)$$

It should be noted that this is an approximation since no real image can truly be both spatially limited and band limited at the same time. For practical purposes, however, this will suffice.

The space-bandwidth product is a measure of the maximum number of distinct elements in an image. If one views the spatial frequency limitation  $\Delta \kappa_x$  as preventing distinct line-pairs which are smaller than

$$\delta x = 1/\Delta \kappa_x \quad (33)$$

from existing, then  $\Delta \kappa_x$  is the resolution in the x direction. Hence, the maximum number of distinct image elements is

$$N = (\Delta x / \delta x)(\Delta y / \delta y) = \Delta x \Delta \kappa_x \Delta y \Delta \kappa_y = SW \quad (34)$$

The advantage of defining the SW for an image is that this quantity is invariant under normal image operations. If an image is shifted or magnified the SW remains the same.

One can define an information density ratio as the ratio of the number of distinct image elements to the space-bandwidth product. The space-bandwidth product does not tell us how much information (in terms of distinct image elements) is located in our image. There are times when a sharp intensity drop-off at the edge of the image elements is required. In this case the spatial bandwidth must be increased beyond

$1/\delta x$ , which increases SW without increasing the number of distinct image elements. Hence the need for also defining the information density ratio.

#### F. RESOLUTION

In this section we will deal with the theory of the resolution of various imaging systems which will be utilized in the design of the optical flip-flop array. The results of this section will be useful in analyzing the required component characteristics and image sizes necessary in order that the flip-flop array will operate.

The resolution of an imaging system is a measure of the minimum distance between two closely spaced point sources which the system is able to resolve into distinct entities in the image. The value of the resolution depends upon the criteria used to determine when the the resulting images are distinct. The criteria used will vary depending upon the system.

There are two imaging systems which will be dealt with in this section: a lens and the light valve. A subsection will be devoted to each. In each subsection the criteria for resolution will be given and the formulas for the resolution stated.

##### 1. LENSES

In this subsection the resolution limits of a lens will be given. When imaging with an ideal lens, there is still a limit to the resolution of the resulting image. This limit can be derived using the Fraunhofer diffraction equation. The result is known as the diffraction limited spot size.



The diffraction limited spot size for a lens is defined by the Rayleigh criteria. The Rayleigh criteria of resolution states that two incoherent point sources are barely resolved (by a diffraction-limited system) when the center of the Airy disk generated by one source falls on the first zero of the Airy disk generated by the second source [17]. Using this, the diffraction limited spot size for incoherent light is

$$\delta = 1.22\lambda d_i / l \quad (35)$$

where

$\lambda$  = wavelength of the light

$d_i$  = image distance

$l$  = diameter of the exit pupil

The limiting form of equation (35) is

$$\delta = 1.22\lambda(f\#) \quad (36)$$

where

$f\#$  = f-number of the lens, which equals the focal length divided by the lens diameter.

A common unit for resolution is line-pairs per unit length, in the same manner as a Ronchi ruling is identified. The resolution in line-pairs per unit length is given by the inverse of twice the spot size. This follows directly from the definition of spot size and need not be elaborated upon here.

## 2. LIGHT VALVE

In this subsection we will deal with the resolution of the light valve. Because of the finite size of the liquid crystals used in the light valve, there is a limit to the resolution of an image recreated by the light valve. This limit will be given in this subsection.

The resolution of the light valve is determined from its spatial point response function which is commonly called the OTF (optical transfer function). The MTF is the modulus of the transfer function. We shall define the spatial bandwidth of the light valve to be the spatial frequency at which the MTF is half of its maximum. Then the minimum resolvable spot size is the inverse of this bandwidth. This bandwidth has been measured to be 750 line pairs per inch (lp/in) [18].

#### G. ANALYSIS OF AN OPTICAL FLIP-FLOP ARRAY

One of the goals of this report is to design an optical system which operates as an optical flip-flop array using optical feedback. In this section the optical flip-flop array will be dealt with in abstract terms. Two areas will be covered. First, a set of conditions sufficient for the creation of an optical flip-flop array using optical feedback will be given and justified. Then, a definition for the alignment tolerance will be presented and discussed.

##### 1. OPTICAL FLIP-FLOP ARRAY CRITERIA

In order to prove that a system will operate as an optical flip-flop array it is necessary to define what is meant by an optical flip-flop array, create a set of criteria sufficient to meet this definition, and then prove that the system meets this criteria. In this section such a definition and set of criteria will be presented and discussed.

The system presented in this report is based upon an optical feedback loop (shown in Figure 1), so the criteria presented here will be specific for this situation. The output of the light valve is imaged back onto the input, so the feedback loop can be considered as an imaging system, which will be useful.

A simple definition of an optical flip-flop array is a spatial array of independent optical flip-flops. This leads us to two sets of criteria: one to ensure the existence of an array of independent elements and the second to assure that every element in that array is an optical flip-flop.

For a system involving imaged optical feedback, as the system in this report does, there are two conditions sufficient for the existence of an array of independent elements. The first is that a device be present in the loop to spatially quantify the area into an array of elements. The second is that the imaging of this array onto itself be one-to-one and onto. This latter condition can be assured if there is no offset nor rotation introduced in the image by the feedback loop and the magnification of the loop is unity. For a practical system it is sufficient if these conditions are met within the tolerance imposed by the spatial quantization.

To ensure that every element is an optical flip-flop, two conditions are sufficient. First, every element must be stable for two intensities of light. Secondly, there must exist some means to change from one intensity to the other and back.

We have determined six criteria which are sufficient to ensure the operation of an imaged feedback loop as an optical flip-flop array. They are summarized below:

1. Device within the loop to spatially quantify the area into array elements.

2. Negligibly small offset introduced in an image by the feedback loop.
3. Negligibly small rotation introduced in an image by the loop.
4. Unit magnification (within tolerance) by the loop.
5. Intensity bistability for every element within the array.
6. The ability to change from one stable intensity to the other and back for every element in the array.

Notice that the first five criteria are sufficient to create an array of optically bistable elements. We shall use this fact in Chapter III.

## 2. ALIGNMENT TOLERANCE

In this subsection the tolerance with which the feedback loop shown in Figure 1 must be aligned in order to operate as an optical flip-flop array will be examined. This tolerance is determined in part by the image guide, since the fibers of the image guide are responsible for quantizing the image. It will be shown that the tolerance is determined by the width of the cladding separating these fibers, the resolution of the feedback loop imaging system, and the fiber array distortion of the image guide.

The tolerance for this system is the degree to which we can deviate from ideal one-to-one and onto imaging around the feedback loop without affecting the practical one-to-one and onto imaging required for independence of the array elements. We will use this to determine the tolerance with which this system must be aligned.

To ensure total independence of the elements in the array, we would like to have the fiber output in the plane IGo image only onto its own

input in the plane  $IG_i$ , but this is not possible. If it were, then each fiber would be part of its own independent feedback loop, because the input to each fiber would only depend upon its own output. However, since an image can not be both space- and band-limited simultaneously, and any imaging system has a finite spatial bandwidth, then some light, however small, from the output of each fiber will extend beyond the boundaries of its own input.

Failing total independence of the fiber-feedback loops, we are left with maximizing the cross-coupling signal-to-noise ratio (SNR) at the input of each fiber. The signal is the light corresponding to that fiber's output. The cross-coupling noise is the light corresponding to every other fiber's output. There will be other noise but the cross-coupling noise is the only noise that can be reduced through better alignment. Independence can be measured in terms of the stability of the individual flip-flops. The lower the SNR, the more dependent the state of a fiber-feedback loop becomes upon the states of its neighbors and hence the less stable it is.

The system will be considered aligned when the SNR at the input of every fiber is sufficiently large to ensure stability. Because this system is intensity bistable some noise can be tolerated, but if the intensity of the noise is large enough to shift a fiber-feedback loop from the dim to the bright stable state, then it is too strong. Similarly, if the intensity of the signal is too low to maintain the bright stable state, then the signal intensity is too weak. Since we are dealing with a regular array, a decrease in the signal intensity due to misalignment will be accompanied by an increase in the noise level, so SNR is a useful parameter.

The SNR is maximized if the image of each fiber's output is centered upon its own input. Define the spot size of the image of the fiber output as the width of the image where a significant intensity of light is present (significant in terms of the SNR). Centering the spot on the input of its fiber will place a maximum distance between the edge of the spot and the input of the adjacent fibers (or minimize the overlap of the spot size onto adjacent fibers). This will minimize the noise coupled into the rest of the fibers.

The alignment tolerance is the difference between the diameter of the fiber including cladding and the spot size of the image of the fiber output. The cladding surrounding a fiber provides a buffer zone where the spot size can extend beyond the input of the fiber without coupling into an adjacent fiber. The difference between this width and the width of the spot size is how far the spot can be offcenter of the fiber input without coupling into an adjacent fiber.

This tolerance is the minimum accuracy with which the magnification, offset, and rotation of the loop must be adjusted. If there is a difference between the fiber array at the input of the image guide and the array at the output of the image guide (i.e. a distortion introduced by the image guide), then the spot sizes will not center exactly upon the fiber inputs regardless of how accurately the system is aligned. In this case the tolerance is reduced by the amount of the distortion.

This alignment tolerance can be maximized if high resolution optics are used to convey the image around the feedback loop. The higher the resolution of the optical system involved, the higher the

spatial frequencies which will be present in the resulting image. This means a sharper edge at the images of the fibers which means a smaller spot size (i.e. less spreading of the images). In this case "high" resolution is relative to the minimum resolution needed to resolve the space between adjacent fibers (the minimum cladding width).

In summary, it can be seen that the alignment tolerance of the feedback loop is controlled by three factors. These are: cladding width, resolution of the feedback loop, and fiber array distortion.

#### H. SUMMARY

In this chapter we discussed and developed theories in six areas which will be needed in the development and analysis of the image guide-based optical flip-flop array. The operation of the light valve was discussed and the response under feedback developed, culminating in the proof of the existence of at least one and normally two stable states under feedback. Next, image guides were discussed. Then, a lens system was analyzed for the effect upon magnification and lens position of small perturbations in object and image distances. Following that, the concept of space-bandwidth product was introduced and explained. Next, the resolution for two imaging systems (a lens and the light valve) was discussed and results given. Finally, an optical flip-flop array created using optical feedback was analyzed. A set of criteria sufficient for the existence of such an array was presented and the alignment tolerance for such a design discussed.

## CHAPTER III

### APPARATUS

#### A. INTRODUCTION

Having presented the relevant theories, the next step is to present the apparatus. In this chapter the design of the image guide-based optical flip-flop array is presented and its operation discussed.

The apparatus and its operation will be covered in two sections. In Section B the optical flip-flop array design will be presented and the operation and interactions of each of its components will be discussed. This includes showing that this design will operate as an optical flip-flop array. Then in Section C the imaging and alignment of the system will be covered, utilizing the degrees of freedom and useful configurations which are part of this design.

#### B. COMPONENT OPERATION AND INTERACTION

Understanding how each component operates and interacts with the rest of the components is the first step in understanding the operation of a system. This section contains that information for the optical flip-flop array. The design for the image guide-based optical flip-flop array will be presented here, the operation and interaction of its components will be discussed, and it will be proven that this design will operate as an optical flip-flop array.



The complete design for the image guide-based optical flip-flop array as it was implemented is given in Figure 5. Plate II shows a photograph of the implemented system. This design is quite complicated at first glance, but becomes easier to interpret once the operation of the subsystems within the design are understood. In the center of this design is the feedback loop (highlighted) containing the light valve and the image guide. This is the heart of the optical flip-flop array. The rest of the components form subsystems concerned with illumination, information input/output, alignment, etc. These subsystems are: feedback loop, information input and output, light source, input viewing configuration, IGo viewing configuration, and IGi viewing configuration. The operation of each of these subsystems will be subsequently explained in separate subsections.

The information on this system is summarized in three tables. Table 1 contains information on the lenses which were used in this design. Table 2 contains information on the remainder of the components used in this design. Table 3 contains information on the imaging from one image plane to another within this system. The distances involved are given, as are the magnifications.

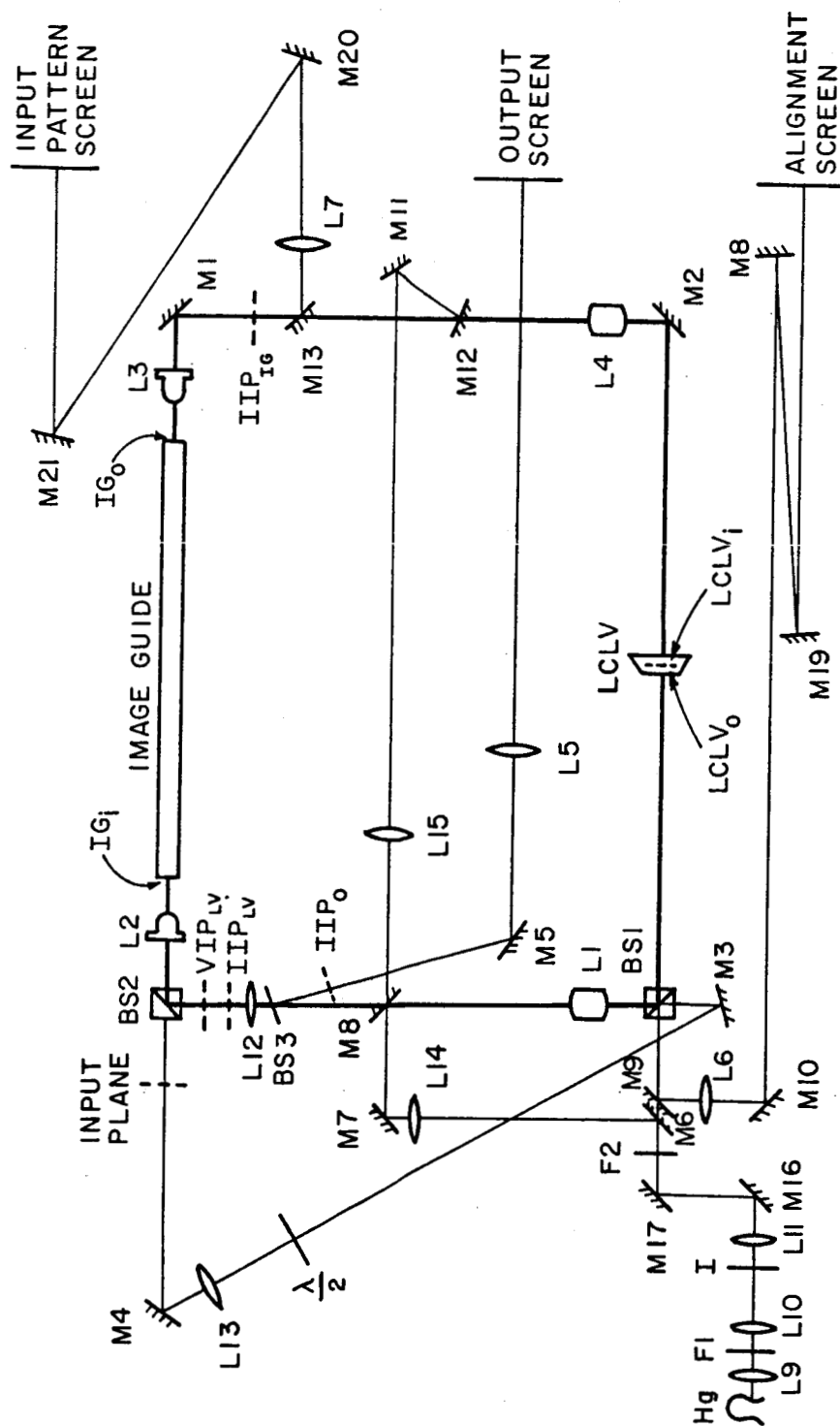


Fig. 5: Sketch of the complete design for the image guide-based optical flip-flop array.

Plate II: Photograph showing the optical flip-flop array system.

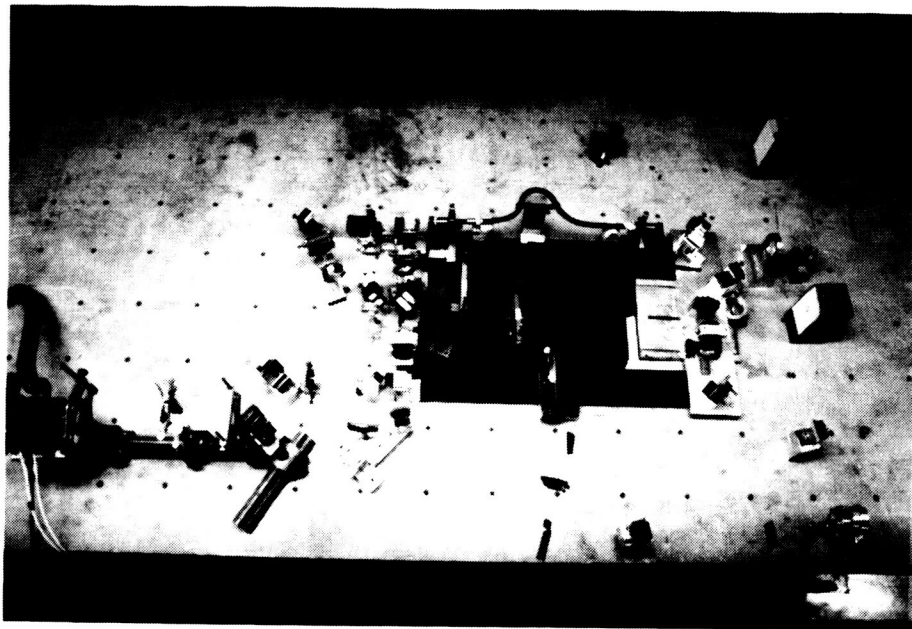


TABLE 1

## LENSES

Symbol	Description
L1	4-element copying lens dia. = 45mm, f.l. = 155mm b.f.l. = 130mm, f.f.l. = 130 mm
L2	20x microscope objective
L3	20x microscope objective
L4	4-element copying lens
L5	4-element copying lens
L6	biconvex lens: dia. = 60mm, f.l. = 390mm
L7	biconvex lens: dia. = 50mm, f.l. = 150mm
L9	biconvex lens: dia. = 50mm, f.l. = 60mm
L10	biconvex lens: dia. = 50mm, f.l. = 120mm
L11	biconvex lens: dia. = 50mm, f.l. = 120mm
L12	biconvex lens: dia. = 38mm, f.l. = 50mm
L13	biconvex lens: dia. = 50mm, f.l. = 160mm
L14	biconvex lens: dia. = 38mm, f.l. = 106mm
L15	biconvex lens: dia. = 50mm, f.l. = 150mm

TABLE 2  
SYSTEM COMPONENTS

Symbol	Description
LCLV	Hughes Liquid Crystal Light Valve. Driven by an audio-oscillator at 1000HZ with a series capacitor to filter DC voltage.
Image Guide	Gallileo flexible image guide. Length = 22", Face is quarter-inch square. Fibers: square-packed core diameter = 0.50 mils minimum cladding width = 0.025 mills
Hg	100W mercury arc lamp
M1, M2, ..., M21	Plane mirrors (19 total)
BS1, BS2	1" Glan-Thompson Beamsplitter cubes
BS3	Pellicle beamsplitter: dia. = 2 in.
F1	Ultraviolet filter: dia. = 50mm
F2	546.1 nm filter: dia. = 25mm
I	Adjustable iris. Diameter adjusted to 2mm
Input Plane	100 $\mu$ m pinhole mounted in spatial filter holder
$\lambda/2$	Half-wave plate

TABLE 3  
IMAGING INFORMATION

Object Plane	Image Plane	Distance	Magnification
LCLVo	VIP <sub>LV</sub>	323mm	0.74
VIP <sub>LV</sub>	IIP <sub>LV</sub>	28mm	0.60
IIP <sub>LV</sub>	IGi	171mm	0.060
IGo	IIP <sub>IG</sub>	204mm	17.
IIP <sub>IG</sub>	LCLVi	711mm	2.2

## 1. FEEDBACK LOOP

In this subsection the operation of the feedback loop shown in Figure 6 will be considered. A photograph of this feedback loop is shown in Plate III. The feedback loop is the heart of the optical flip-flop array, being responsible for creating the array of bistable optical devices. The feedback loop is as an imaging system since it images the input of the light valve back onto itself. It also is a system to produce an array of bistable elements. Thus, its operation can be separated into three parts: imaging relationships of its components; the degrees of freedom (translation, orientation, and magnification) present in the design of this system; and its operation as an array of bistable optical elements.

First, the imaging relationships within the feedback loop will be considered. There are seven image planes within this loop and seven systems to image from one to the next. The image planes are: LCLVi (the input plane of the light valve), LCLVo (the output plane of the light valve), VIP<sub>LV</sub> (a virtual image plane), IIP<sub>LV</sub> (an intermediate image plane), IGi (the input plane of the image guide), IGo (the output plane of the image guide), and IIP<sub>IG</sub>. The imaging systems involved in the transfers are, respectively, the light valve, lenses L1, L12, and L2, the image guide, and lenses L3 and L4.

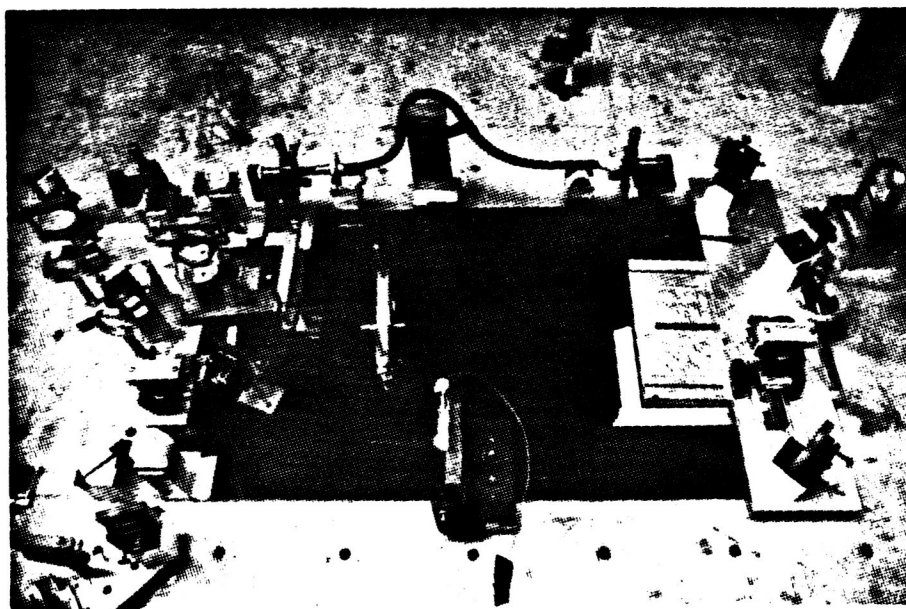
BS1 and BS2 are Glan-Thompson beamsplitters. BS1 is used as a pair of crossed polarizers without which the light valve would not act as an amplifier (as explained in Chapter II, Section B). BS2 operates as a mirror in this situation. The light in the feedback loop will reflect off of it because this light has already been polarized by





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Plate III: Photograph showing the feedback loop and information input and output subsystems.



reflecting off of BS1. The reason a beamsplitter is used in this spot instead of a mirror is to enable an information input into the system (as explained in the next subsection).

Now that the imaging relationships for the feedback loop are understood, we shall examine the degrees of freedom designed into this imaging system. The magnification, translation, and orientation of an image are all adjustable. These adjustments are useful when imaging and aligning this system.

The magnification of an image at LCLVi by the feedback loop is affected by the magnification from IIP<sub>IG</sub> to LCLVi and hence is adjustable. Mirrors M1 and M2 and lens L4 are located on a large translational stage which moves parallel to the optical axis of light entering M1 and leaving M2. Adjusting this translational stage adjusts the path length between IIP<sub>IG</sub> and LCLVi without affecting the path of light in the rest of the system. Furthermore, Lens L4 is mounted on an additional translational stage which moves parallel to the optical axis of L4 and thus can be adjusted to continue imaging IIP<sub>IG</sub> onto LCLVi even when the path length has been changed. This situation was analyzed in Chapter II, Section D. The relationship between changes in the path length and changes in the magnification were derived as was the change in lens position required to maintain imaging. Since the magnification from IIP<sub>IG</sub> to LCLVi can be adjusted in this manner, the magnification of the loop can be adjusted.

The offset introduced in an image at LCLVi by the loop can be adjusted by the tilt of mirror M2. The light from the original image reflects off of mirror M2 before reimaging onto LCLVi, so any

adjustment in the orientation of M2 will introduce an offset in the position of the new image at LCLVi. Since mirror M2 can be tilted about both the vertical and horizontal axes, an offset in any direction is achievable.

The change in orientation of an image at LCLVi by the loop can be adjusted if a flexible image guide is used. With a flexible image guide it is possible to change the orientation of IGo with respect to IGi. Thus, the change in orientation due to the feedback loop can be adjusted.

Now that the degrees of freedom of the feedback loop have also been covered, it is evident that this feedback loop can operate as an array of bistable optical elements. In Chapter II, Section G a set of criteria was given for an optical flip-flop array, the first five of which were sufficient to create an array of bistable optical elements. The image guide spatially quantifies the loop into an array corresponding to the array formed by its fibers at IGo, thus satisfying the condition of spatial quantification. The offset, rotation, and magnification of an image can all be adjusted for this loop, hence these conditions are also satisfied. Finally, in Chapter II, Section B, it was shown that it is possible to achieve intensity bistability for any point on the image guide through feedback of this sort. This satisfies the last condition, hence this system will operate as an array of bistable optical elements.

## 2. INFORMATION INPUT AND OUTPUT

The information input and output for this system are shown in Figure 7. A photograph of this subsystem is contained in Plate III.

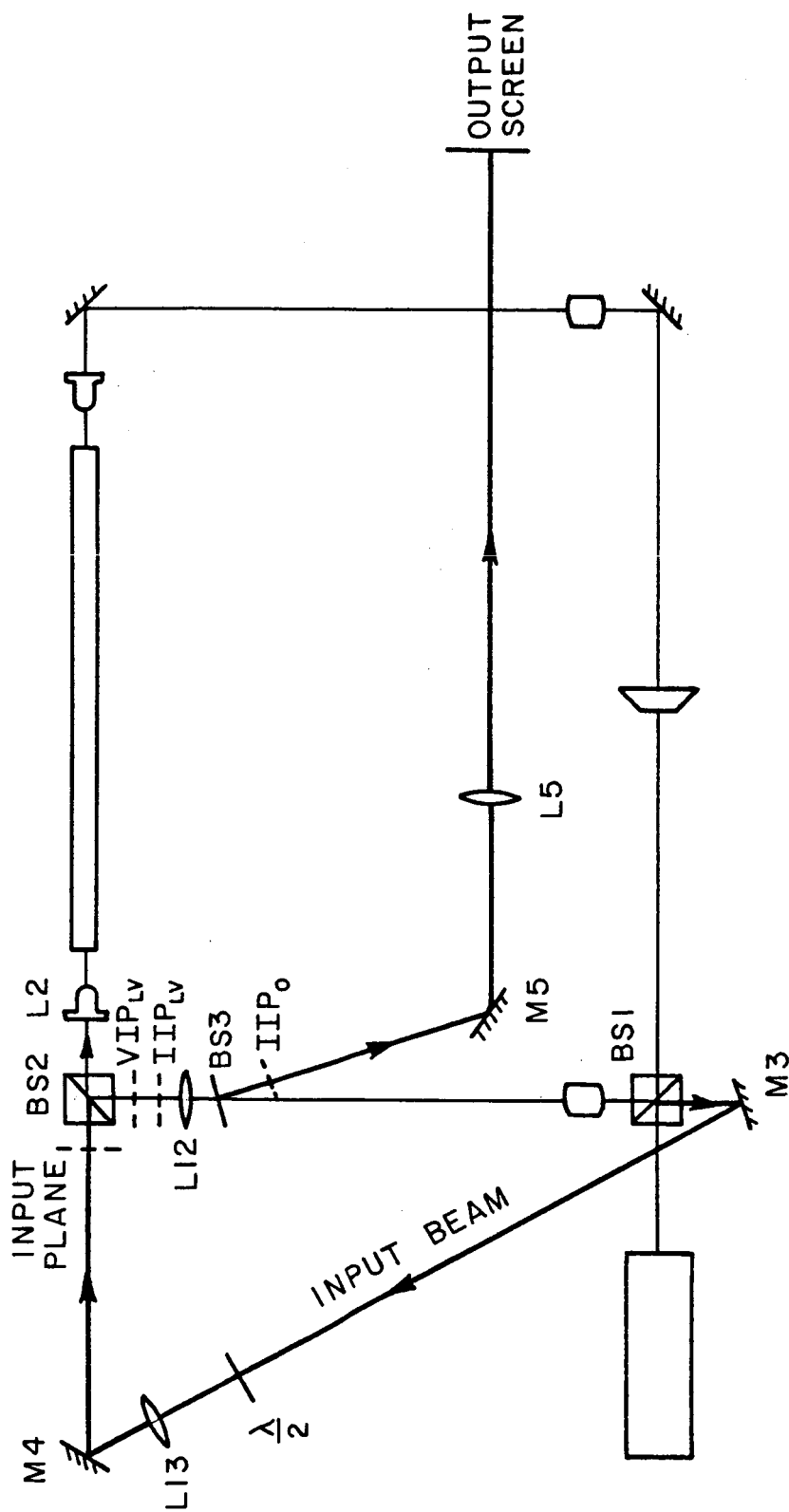


Fig. 7: Sketch of the information input and output subsystem.

This subsystem is used to set the flip-flops and observe the states they are in during operation. The information input for this system consists of a single spot of light used to set the desired flip-flop. The information output for this system consists of an image of LCLVo, which contains the states of the individual flip-flops.

The information input apparatus operates as follows. The Input Plane is illuminated with the light from the source which is initially the wrong polarization to pass through BS1. This light is redirected, using mirrors M3 and M4, and passed through a half-wave plate to rotate its polarization 90°. Then it illuminates the Input Plane, passes through BS2 and enters the feedback loop. The Input Plane is located the same distance from lens L2 as IIP<sub>Ly</sub> is located. Hence, any illuminated pattern located in the Input Plane will be imaged onto IGi via lens L2, because IIP<sub>Ly</sub> is imaged onto IGi via lens L2. Since IGi is imaged onto LCLVi, the pattern in the Input Plane is also imaged onto LCLVi.

The flip-flops can be set through using this information input. The feedback loop creates an array of bistable optical elements (as discussed in Subsection 1). In Chapter II, Section B it was shown that each bistable element could be placed in the bright stable state (i.e. set) by illuminating the corresponding area of the light valve input with additional light. Therefore, this information input will set the desired flip-flop. The fact that the information input beam has the opposite polarization of the Data beam does not matter because the fibers of the image guide are not polarization preserving and the input of the light valve is not polarization sensitive.

To clear the flip-flops, the input to the light valve is blocked. It was shown in Chapter II, Section B that this is sufficient to place the flip-flops in the dark (cleared) stable state.

Lens L13 is used as a field lens. It concentrates the Input beam onto the Input Plane thus increasing the intensity of the Input beam.

In order to selectively input to this system, the Input Plane contains a 100  $\mu\text{m}$  pinhole mounted in a spatial filter holder. This pinhole images onto just a single fiber input at IGI and hence onto the area of the light valve corresponding to that fiber. Thus, it enables each flip-flop in the system to be individually set. The choice of flip-flop is made by adjusting the position of the pinhole.

The information output for this system, which is also shown in Figure 7, operates as follows. BS3 is a pellicle beamsplitter which redirects part of the data beam into the output beam. IIP<sub>0</sub> is an intermediate image plane. LCLVo is imaged onto the Output screen via lenses L1 and L5, thus serving as an output for the operating optical flip-flop array.

The light which is lost due to BS3 is not critical. The addition of BS3 merely serves to increase the attenuation of the loop slightly. This increase in attenuation will shift the stable operating intensities only slightly, as can be seen from our analysis of the light valve under feedback (Chapter II, Section B).

The position of BS3 within the loop is optimized in terms of minimum loss of light balanced with attaining the brightest output. If BS3 is located in the Read beam it will split off light twice (once as

the Read beam enters and once after it has reflected off of the LCLV) and a polarizer would be required to filter out the pattern. If BS3 is placed in the beam at a later position in the loop, reflections off of the optical components within the loop will cause a decrease in the intensity of the output as will the attenuation of the image guide. The position shown appears to be optimal in terms of minimum loss of light and brightest output.

### 3. LIGHT SOURCE

In this subsection the operation of the components which comprise the light source for this system will be explained. The primary source beam for this system is generated by a mercury arc lamp. A system of lenses and filters was designed to best utilize this source.

The light source, shown in Figure 8, operate as follows. L9 is a condenser lens, gathering the light emitted by the mercury arc lamp. F1 is an ultraviolet filter, screening out radiation which is harmful to the LCLV and to the people working with the system. L10 images the arc of the mercury lamp onto the plane of the iris. The iris is adjusted to the dimensions of this image so as to best approximate a point source without losing any significant light. Then L11 collimates the resulting beam as best as possible considering the finite source size. Mirrors M16 and M17 are used to align the source beam along the optical axis of the system. F2 is a 546.1 nm filter. This filter was chosen because the LCLV is sensitive to this wavelength. In this manner a reasonably collimated beam of green light is generated to provide illumination for this optical flip-flop array.

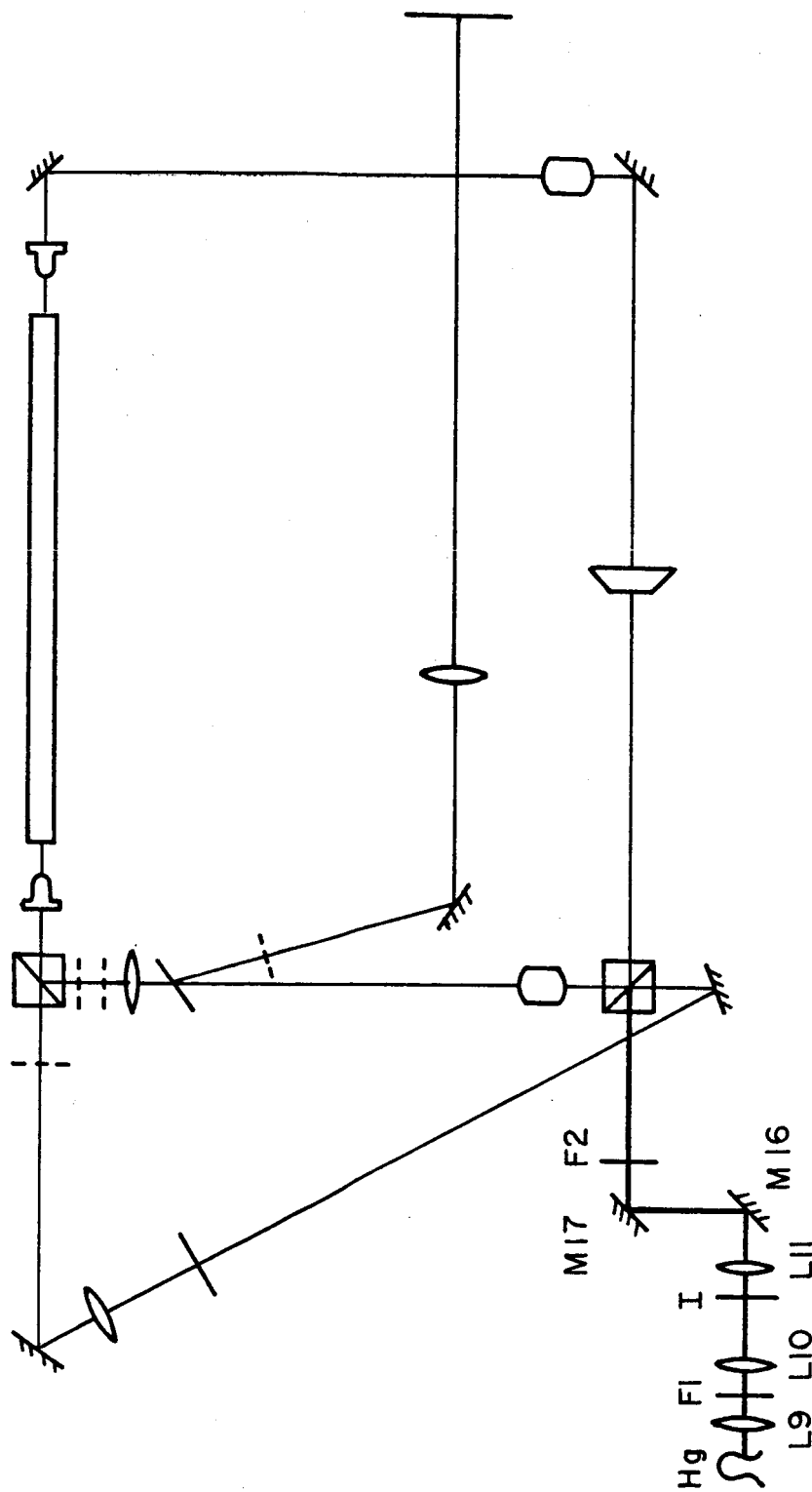


Fig. 8: Sketch of the light source subsystem.



It should be noted that this light source is not ideal. The generated beam is not truly collimated nor is it completely uniform in intensity. It was chosen for high intensity with a minimum of nonuniformity.

#### 4. IMAGE GUIDE INPUT VIEWING CONFIGURATION

The operation of the image guide input viewing configuration portion of this design is explained in this subsection. This configuration is used to view the area of the image guide into which the light from the Input Plane or the light in the feedback loop is coupling. This information is useful in the initial selection of an image guide operating area and later in observing which fibers are illuminated by the information input beam.

The image guide input viewing configuration is the first of three reconfigurations of the original feedback loop, reconfigurations done for alignment and analysis purposes. They are not used when the flip-flop array is operating. The reconfigurations are accomplished by using removable mirrors whenever the presence of a mirror would block the light in the feedback loop. These mirrors will be identified as such.

The image guide input viewing configuration is shown in Figure 9. A photograph of the implemented configuration is contained in Plate IV. The apparatus on the left is for selectively coupling into the image guide and has already been discussed in Subsections 1 and 2. Lens L7 images  $IIP_{IG}$  onto the Input Viewing Screen via mirrors M13, M20 and M21. (Mirror M13 is removable.) Since  $IIP_{IG}$  contains the image of  $IG_0$ , it

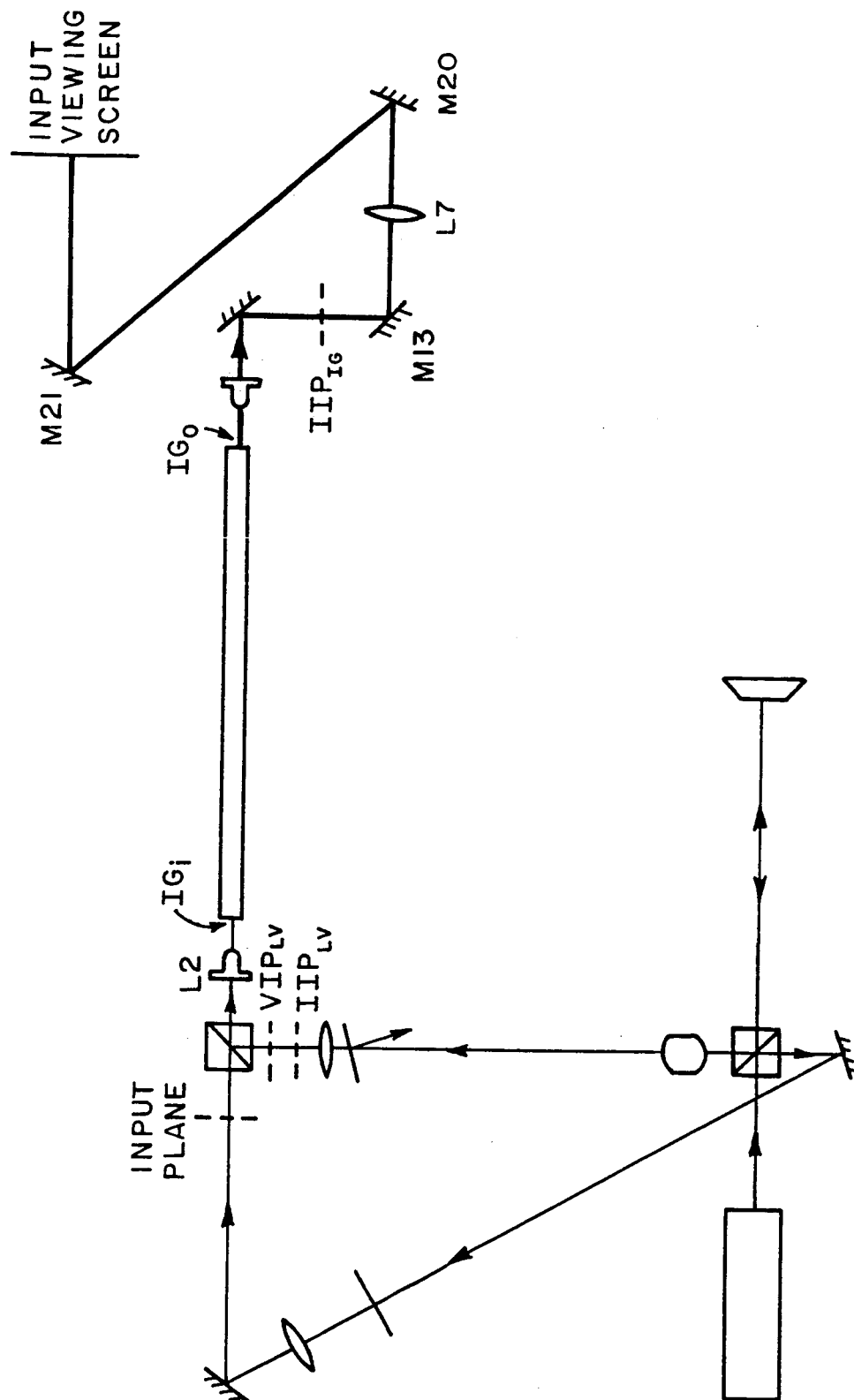
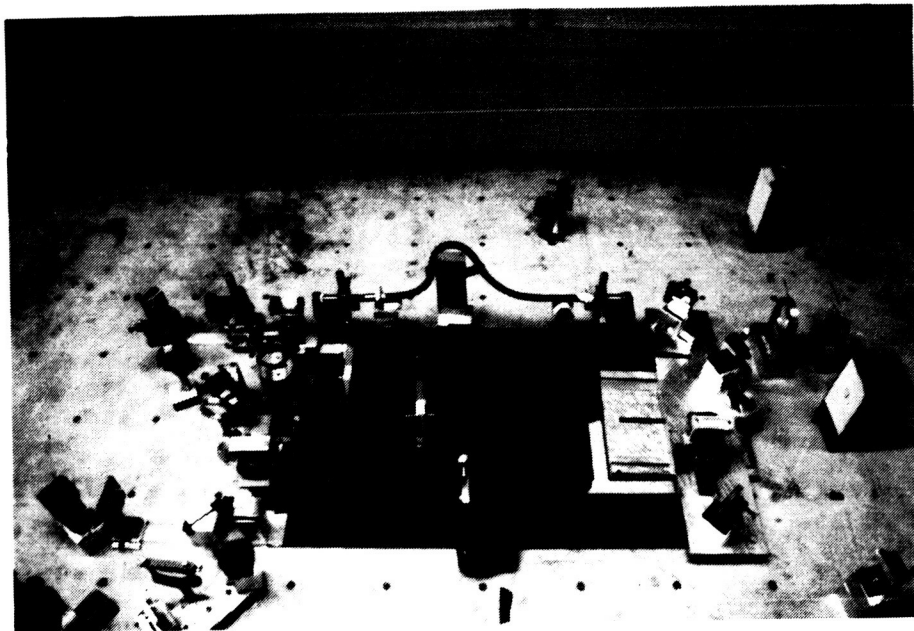


Fig. 9. Sketch of the image guide input viewing configuration subsystem.

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Plate IV: Photograph showing the image guide input viewing configuration subsystem.



is possible to view the output of the image guide using this configuration and determine the fibers into which light is coupling. Because of the design of this configuration, the input to the image guide may be from the Input Plane or from LCLVo (but not during feedback). If it is desired to use this during feedback, then mirror M13 must be replaced by a beamsplitter, in which case this becomes an alternative output.

## 5. IGo VIEWING CONFIGURATION

In this subsection the operation of the IGo viewing configuration will be explained. This is the second of the reconfigurations of the feedback loop. It is utilized in imaging IGo onto LCLVi and in the detailed alignment of the image guide in the feedback loop.

The IGo viewing configuration, which is shown in Figure 10, is used to image IGo onto the Alignment Screen. A photograph of the implemented configuration is contained in Plate V. The source beam is redirected using mirrors M6, M7 and M8 so that it retraces the path of the data beam backwards. (Mirrors M6 and M8 are removable.) Lens L14 is used to negate the effect of lens L1 so that the source beam will remain collimated. Part of it will be reflected by BS1 and become the Read beam. The rest will pass through BS1 and become the information input beam, illuminating the image guide. (Since this input beam has passed through BS1 instead of reflecting off of it as before, we must remove the half-wave plate, shown in Figure 7, from the information input beam path.) The image of LCLVi will be carried by the Read beam reflecting off of the light valve output and passing through BS1. Lens L6 images LCLVo onto the Alignment Screen via mirrors M9 (which is

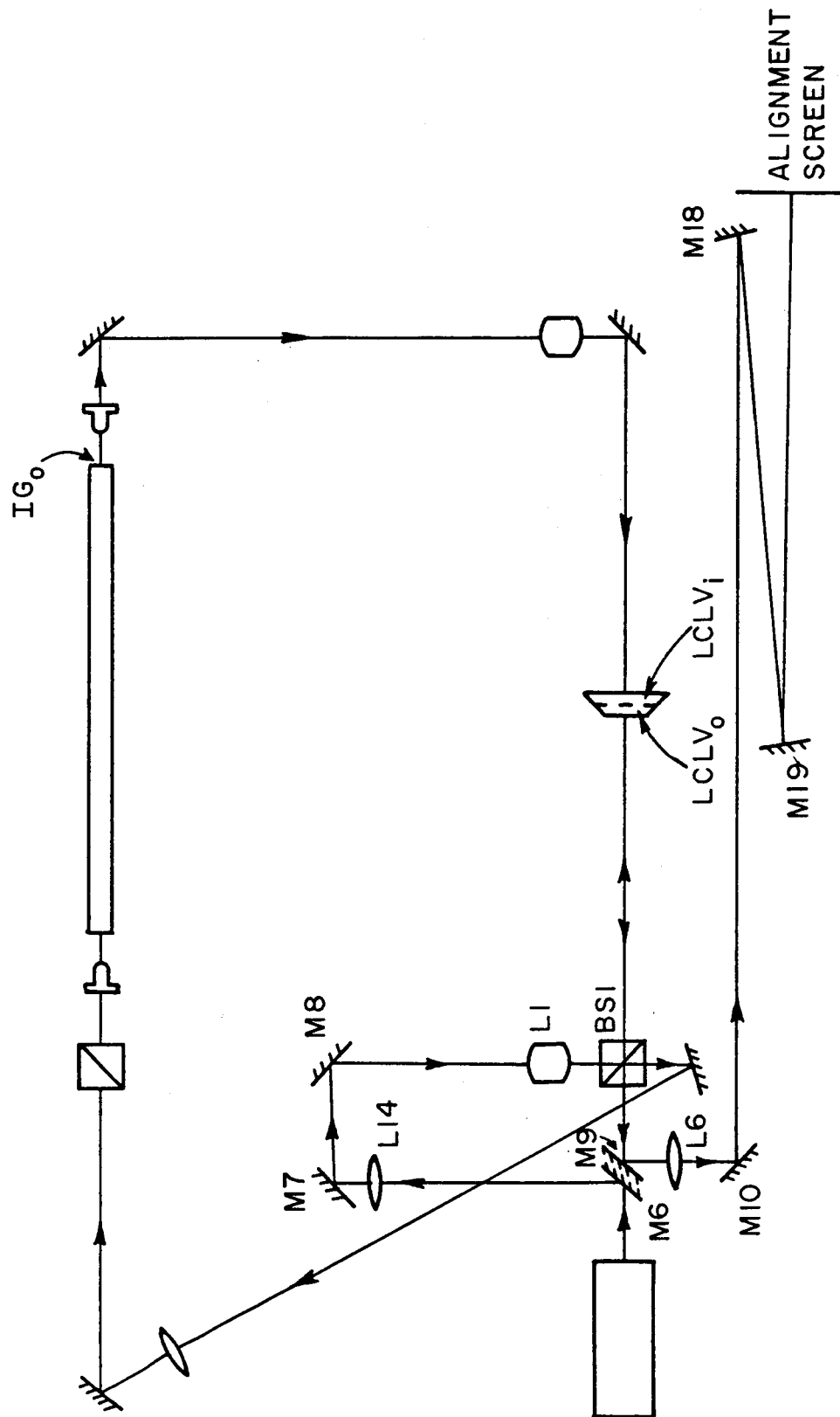
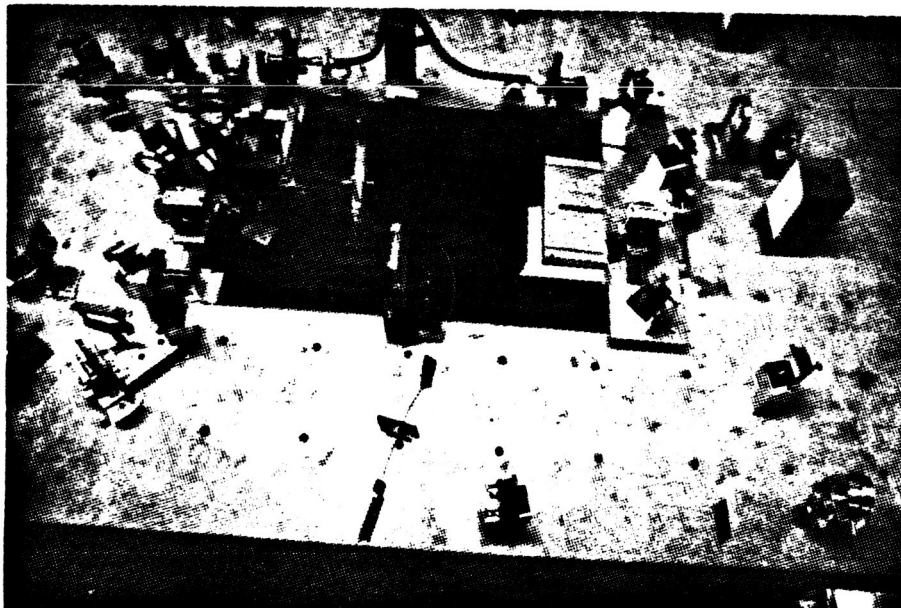


Fig. 10: Sketch of the IGo viewing configuration subsystem.

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Plate V: Photograph showing the IGo viewing configuration subsystem.



removable), M10, M18, and M19. Hence, the Alignment Screen contains the image of LCLVi. We saw when examining the feedback loop that IGo is imaged onto LCLVi so we have the result that IGo is imaged onto the Alignment Screen as desired.

## 6. IGi VIEWING CONFIGURATION

In this subsection the operation of the IGi viewing configuration will be explained. This is the last of the reconfigurations of the feedback loop. It is utilized to image LCLVo onto IGi and in the detailed alignment of the image guide in the feedback loop.

The IGi viewing mode, which is shown in Figure 11, is used to image IGi onto the Alignment Screen. A photograph of the implemented configuration is contained in Plate VI. This configuration is very similar to the IGo viewing configuration except that mirror M8 has been removed and mirror M11 and the removable mirror M12 have been added. Mirrors M11 and M12 redirect the source beam backwards along the path of the feedback beam, thus illuminating the image guide backwards. Lens L15 is used to negate the effect of lens L14 so that the source beam remains collimated. LCLVo has already been made conjugate to IGi (Subsection 1) and the Alignment Screen (Subsection 5). Therefore IGi is imaged onto the Alignment Screen as desired.

## 7. SUMMARY

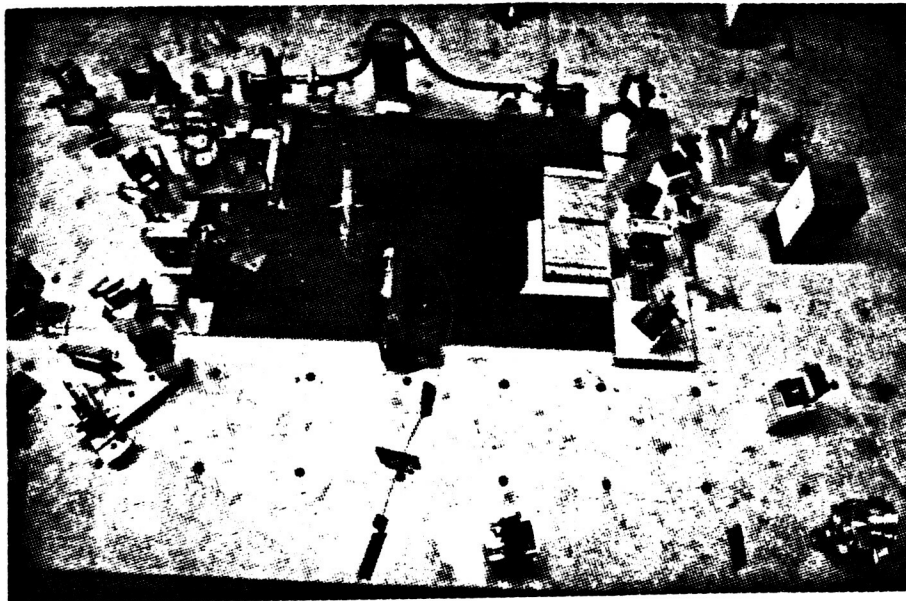
In this chapter the complete design of the image guide-based optical flip-flop array was presented and its operation discussed. This design was separated into six subsystems (feedback loop, information input and output, light source, image guide input viewing configuration,





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Plate VI: Photograph showing the IGi viewing configuration subsystem.



IGo viewing configuration, and IGi viewing configuration). The application and operation of each subsystem was discussed. The actual optical flip-flop array is formed by the feedback loop combined with the information input.

### C. IMAGING AND ALIGNMENT

In this section the imaging and alignment procedure utilizing the IGo and IGi viewing configuration subsystems will be presented and explained. Imaging and aligning correspond, respectively, to the axial and transverse adjustments necessary before operating a system. The need for these subsystems to make these adjustments will be briefly discussed. Imaging will then be dealt with followed by aligning.

The additional components in the IGo and IGi viewing configuration subsystems were necessary due to the presence of the image guide in the feedback loop. Because of the averaging and spatially quantizing nature of its transmission, viewing the output of the image guide does not allow one to determine when an object has been imaged and aligned within tolerance onto the input of the image guide if this tolerance is smaller than the width of a fiber core. The feedback loop has an alignment tolerance smaller than the width of the cladding of the image guide (as discussed in Chapter II, Section G, Subsection 2) which, for the image guide used (and for image guides in general), is much less than the width of a fiber core. Therefore, an imaging and alignment procedure was designed whereby the feedback loop (and the rest of the system) could be imaged and aligned despite the presence of the image guide.

Imaging the complete system (shown in Figure 5) is accomplished in three steps, the first of which is to roughly position all of the lenses while in the normal (feedback) configuration. This can be accomplished from mathematical calculations.

The second step is to place the system in the IGo viewing configuration (shown in Figure 10) in order to adjust lenses L4 and L6 for imaging. This is accomplished by inserting mirrors M6, M8, and M9 and removing the half-wave plate. Lens L4 is adjusted until IGo is imaged onto LCLVi. Lens L6 is adjusted until LCLVo is imaged onto the Alignment Screen. Since the light valve does not transmit light, these adjustments can be made independently, even though the pattern of the fibers at IGo will serve as a reference for both and the Alignment Screen will be used to view both for determining when each is imaged.

The third step is to place the system in the IGi viewing configuration (shown in Figure 11) in order to adjust lens L1 for imaging and to locate the Input Plane. This is accomplished by removing mirror M8 and inserting mirror M12. The Input Plane is located by observing where IGi is imaged by lens L2. Lens L1 is adjusted until IGi is imaged onto the Alignment Screen. Since air is a homogeneous medium, and LCLVo is imaged onto the Alignment Screen (step 2), then IGi is imaged onto LCLVo and vice-versa.

At this point all of the imaging has been accomplished. Aligning the system comes next.

The first step in aligning the system is to record the position and orientation of the image of IGi in the plane of the Alignment Screen. This is accomplished by replacing the Alignment Screen with

slide film (we are still in the IGi viewing configuration), exposing it, developing it, and then replacing it in the plane of the Alignment Screen. Mount the developed slide in back of a piece of frosted glass. Looking through the back of the slide it is possible to view the image of IGi (formed on the frosted glass) and position the slide so that it superimposes upon the image from which it was created. The slide will now serve as a record of the location and orientation of the image of IGi.

The next step is to return the system to the IGo viewing configuration in order to perform the actual alignment. None of the imaging relationships have been altered by changing configurations. Therefore, by adjusting the image of IGo until it superimposes upon the slide of IGi, we are simultaneously adjusting the image of IGo until it superimposes upon IGi itself (i.e. aligning the system). We can adjust the orientation, position and size of the image of IGo by adjusting the loop rotation, offset and magnification (as discussed in Section B, Subsection 1). Once the image of IGo is superimposed upon the slide of IGi within the required tolerance (which is defined in Chapter II, Section G, Subsection 1), the system is aligned.

To align the system it is necessary to know which bundle of fibers at IGo should superimpose upon a given bundle at IGi. The initial alignment is performed with bundles of fibers because this is not as fine of an array as the array of fibers. Once the bundles are aligned it is easy to determine the microscopic adjustments needed to align the fibers themselves.

Two methods of relating the bundles at IGo to the bundles at IGi were considered. The first method involves placing an aperture in the plane  $IIP_{IG}$ . This aperture will restrict light in both configurations to the same small number of bundles, which can then be aligned upon each other by first aligning the boundary formed by the aperture onto itself. The second method is to use a unique pattern of nontransmitting fibers as benchmarks to ensure that the correct bundles are being aligned upon each other. Since few image guides are perfect over their entire array of fibers, such benchmarks are likely to exist. Both methods work well.

The process for aligning and imaging the system is summarized below:

- 1) Roughly position all lenses and mirrors from mathematical calculations in the feedback mode.

- 2) Configure for the IGo viewing mode by inserting mirrors M6, M8, and M9 and removing the halfwave plate. Adjust lenses L4 and L6 until IGo and LCLVo are imaged onto LCLVi and the Alignment Screen respectively.

- 3) Reconfigure the system for the IGi viewing mode by removing M8 and adding M12. Adjust lens L1 until IGi is imaged onto the Alignment Screen. Locate the Input Plane utilizing the image of IGi.

- 4) Create slide of IGi. Position it.

- 5) Reconfigure the system for the IGo viewing mode by removing M12 and inserting M8. Make rotational adjustment

in IGo. Make magnification adjustment in IGo. Adjust M2 for transverse offset.

6) Remove all of the removable mirrors (M6, M8, M9).

Replace the half-wave plate. The system is now ready to operate.

#### D. SUMMARY

In this chapter the apparatus was presented. The operation of the individual components and the system as a whole was covered. It was shown that the design contained in Figure 5 should operate as an optical flip-flop array. In addition, the imaging and alignment procedure for this design was presented and explained.

## CHAPTER IV

### IMPLEMENTATION AND RESULTS

#### A. INTRODUCTION

At this point we have seen the design of the optical flip-flop array and analyzed it utilizing the theories presented in Chapter II. Now it is time to present the results of implementing this system, thereby confirming through actual data what has until now just been argued theoretically. In this chapter the results of the implementation and operation of this optical flip-flop array design will be given. Also, the characteristics of the image guide will be examined in light of the results of using it in this system.

The contents of this chapter are separated into three topics. First is the implementation of this system. This is covered in Section B where, among other things, the alignment procedure which was developed in this report will be shown to have sufficient degrees of freedom to align the system. The second topic is system operation. Section C contains the results of testing this system once it was made operational. The third topic is analyzing the characteristics of the image guide in terms of their advantages and disadvantages for using the image guide in this or a similar optical system. This is dealt with in Section D.

#### B. IMPLEMENTATION

There are two stages involved in implementing this optical flip-flop array. The first stage is to align the system. The second

stage is to achieve intensity bistability. Once these are accomplished, the system has been implemented. These two stages will be covered in this section.

## 1. ALIGNMENT

In this subsection the successful results of implementing the alignment procedure presented in Chapter III, Section C are given. The heart of this procedure is the use of slide film to record the position of IGi. Thus, in this section we will focus on the use of the slide film. But we will also cover the mismatch between the input and output fiber arrays of the image guide.

The use of slide film in the alignment procedure was carefully checked for three potential problems: distortion, contrast, and resolution. A problem with any of these would prevent us from aligning the system using the slide film. The film which was used was Kodak Ektachrome, 35mm, 200ASA.

Distortion was not a problem. The possibility existed that the image of IGi on the film would be distorted enough during the processing of the film that it could no longer be used as an accurate record of the image of IGi. In order to check this possibility, the slide of the image of IGi was superimposed upon the image from which it was created. There was no observable difference. This can be seen in the photograph in Figure 12. The edges of all of the fibers are sharp, indicating the the images align very well.

The contrast between an image and the slide was likewise not a problem. In order to use the slide for alignment purposes, it is



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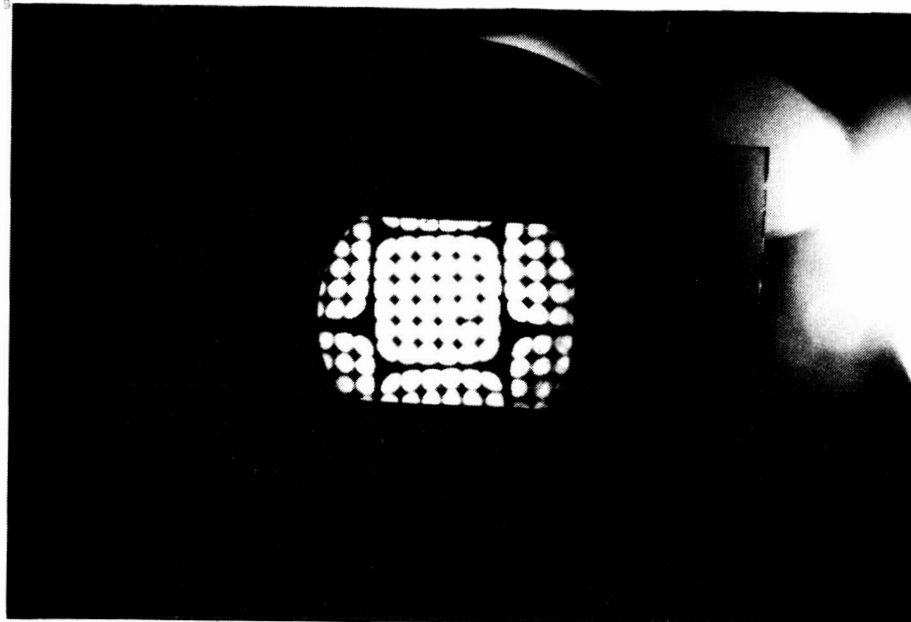


Fig. 12: Photograph showing the comparison, through superposition, between the slide of the image of IGi and the image from which it was created.

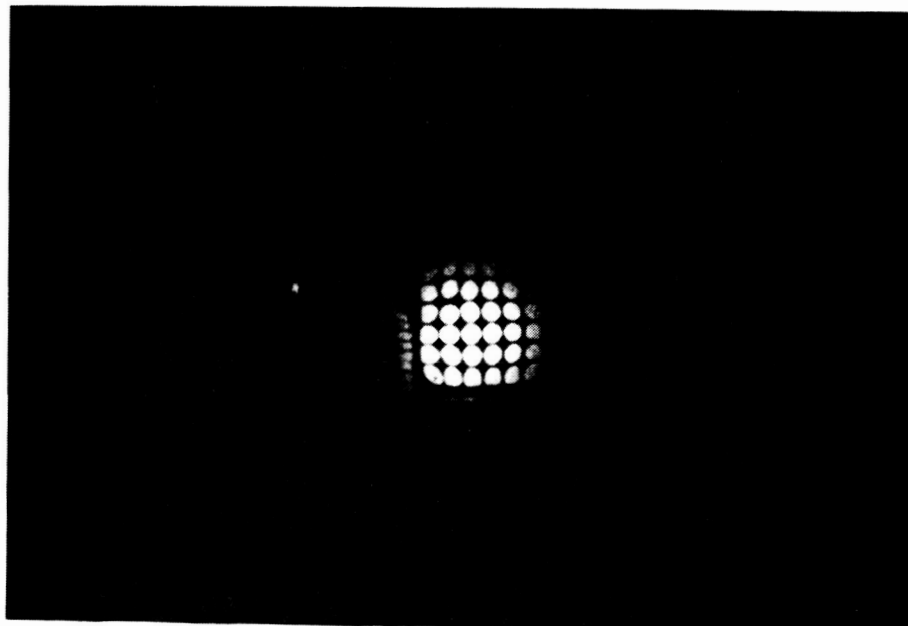


Fig. 13: Photograph showing the comparison between the input and output fiber arrays of the image guide via superimposing the image of IGo onto the slide of the image of IGi.

necessary that there be sufficient contrast between the image and the slide such that misalignments are visible. By experimenting with the exposure time of the slide it was possible to make the slide transparent enough that the image could be seen through it, but not so transparent that the image on the slide was not readily apparent. Thus, both images were clear and misalignments were quite noticeable.

Resolving the misalignment was also not a problem with this method. Misalignments on the order of one fifth of the interstitial space between the fibers were readily visible. Therefore, determining when the system was aligned within tolerances proved quite easy.

The success of the alignment procedure can be seen in Figure 13. Using the alignment components, the image of one bundle of fibers of IGo was aligned onto the same bundle in the slide of IGi. The photograph located in Figure 13 was then taken. The alignment of the central bundle in this photograph can be seen from the sharp edges of the fibers within this bundle. This alignment confirms the ability of the alignment components to compensate for any type of optical misalignment.

The physical mismatch between the input and output fiber arrays of the image guide seriously limited the number of bundles which could be aligned. This mismatch can be seen in the photograph in Figure 13. The central bundle is aligned but the bundle to the right of it (only part of which shows in the photograph) is obviously not aligned. The mismatch between the image of the bundle from IGo and the slide of the bundle from IGi creates a double image effect which results in the dark lines through the middle of the fibers.

Because of the fiber array mismatch, feedback operations were limited to a single bundle of thirty-six fibers. Although not shown in the photograph, all of the surrounding bundles failed to align. Furthermore, there was no pattern to their misalignments. This resulted in only one bundle being able to be aligned at any one time. Therefore, feedback operations were limited to just that bundle of thirty-six fibers. Hence, the system was limited to thirty-six flip-flops.

In summary, the alignment procedure was a success. The slide film proved to be an excellent medium for recording the image of IGI. And the alignment components proved adequate to compensate for all misalignments of the feedback loop. Due to the mismatch between the input and output fiber arrays, however, only a single bundle could be adequately aligned at any one time.

## 2. INTENSITY BISTABILITY

Once the feedback loop is properly imaged and aligned, the final step in implementing the optical flip-flop array is to adjust the system for intensity bistability. In this subsection the achievement of intensity bistability is covered.

The achievement of intensity bistability is demonstrated by the photograph in Figure 14. This photograph shows two flip-flops in the bright state and the rest in the dim state. The photograph was taken via the output of the system of an image which had been stable for over an hour. Furthermore, each of these flip-flops was stable in the dim state as well. This photograph also verifies the proper imaging and aligning of the system.

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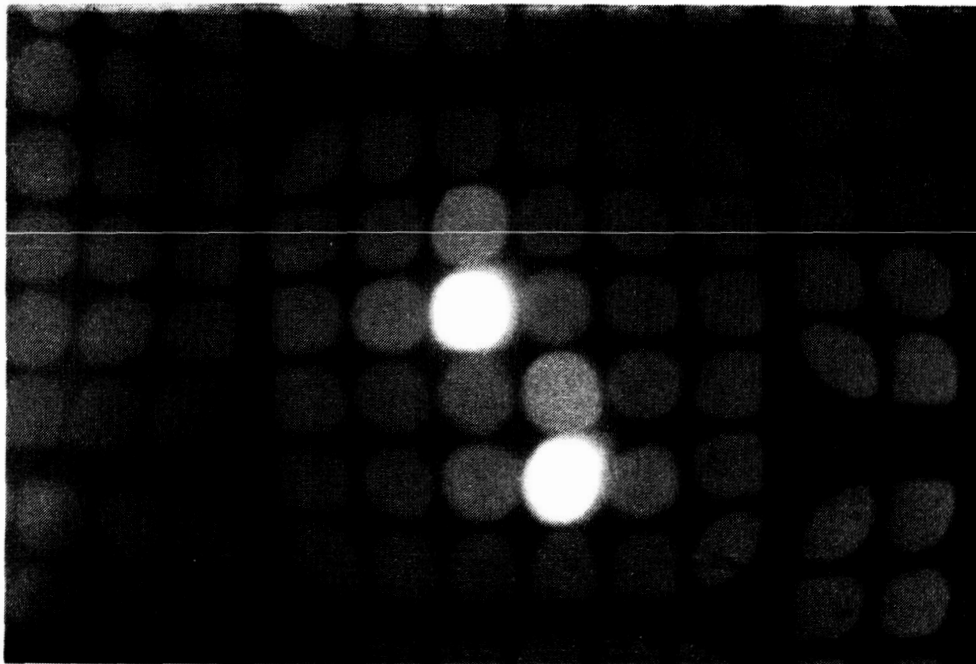


Fig. 14: Photograph demonstrating intensity bistability of the flip-flop array.

The intensity bistability was achieved by adjusting the light valve voltage. Figure 15 shows a plot of the light valve response function for three different voltages. It can be seen that increasing the voltage causes the light valve response curve to shift to the left. (This shift is not a linear function of voltage and the shape of the light valve response curve is voltage dependent but these factors do not affect the ultimate result.) It can be seen that when the voltage is at 5.3 VAC or 8.5 VAC only one stable operating point exists, but when the voltage is at 7.9 VAC there are two stable operating points. Therefore, there is a voltage range over which intensity bistability will exist.

There are two other parameters, the loop attenuation and the Read beam intensity, which can be adjusted to affect the existence of stable states, but these were not utilized because they served only to decrease the voltage range over which bistability existed. The loop attenuation can only be increased and the Read beam intensity decreased, both of which serve to tighten the voltage range over which bistability exists. A tight voltage range is not desirable, so these parameters were left alone.

### C. OPERATION OF THE OPTICAL FLIP-FLOP ARRAY

Having achieved alignment and intensity bistability, the system now operates as an optical flip-flop array. In this section the operation of this optical flip-flop array will be covered. Setting and clearing the flip-flops will be dealt with as will the stability of the array. In addition, photographs of various operating configurations will be presented.

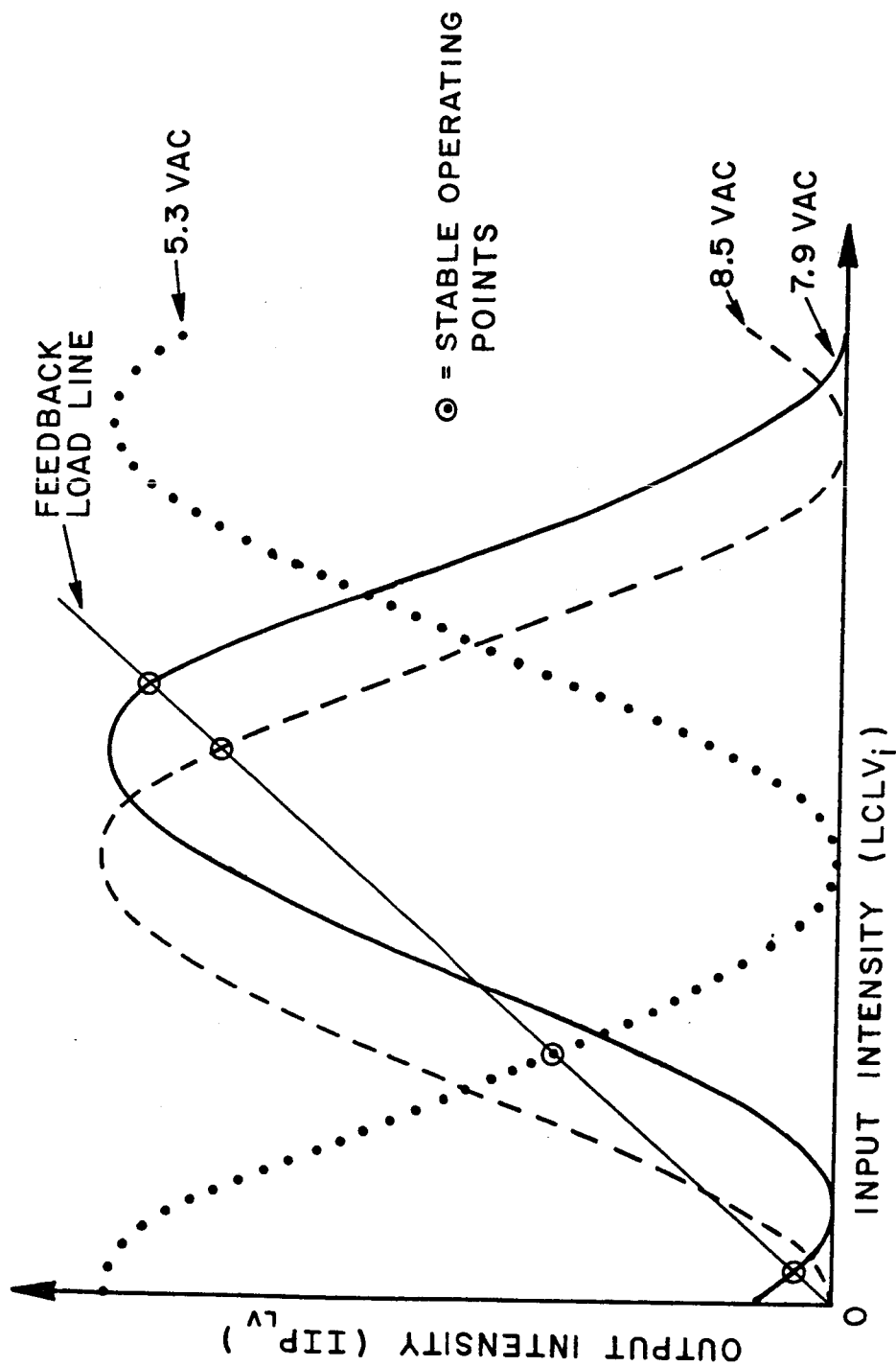


Fig. 15: Plot showing the voltage dependence of the light valve response under feedback.

In order to test this optical flip-flop array, a number of different subsets of the flip-flops within the array were set and the results observed. Figure 14 contains a photograph when just two flip-flops were set. Figure 16 contains photographs of six other configurations of set flip-flops. All thirty-six flip-flops were tried in at least one such configuration.

Setting a flip-flop (i.e. placing it in the bright stable state) was accomplished by using the information input to the system (Figure 7). The pinhole in the Input Plane was adjusted until it occupied a point conjugate to the input of the fiber belonging to the desired flip-flop. Then the pinhole was illuminated by the Input beam until the flip-flop had reached the point where it would decay to the bright stable state when the Input beam was blocked. All thirty-six flip-flops were tested and found to be capable of activation in this manner. Once set, they remained in the bright state until cleared.

Although each flip-flop could be set individually, it was necessary to clear them all simultaneously. Clearing a flip-flop (i.e. placing it in the dim stable state) is accomplished by attenuating the light in the feedback loop of that flip-flop. This was accomplished by blocking the input of light to the light valve. However, this also attenuated the light of all the other flip-flops thus clearing them all simultaneously.

Although not implemented as part of this report, there are several ways to clear the flip-flops individually. Sengupta, et. al. [4] utilized a second light valve (actually the lower half of the same light valve) in the feedback loop and were able to clear a flip-flop by illuminating the appropriate spot on the input to this second light

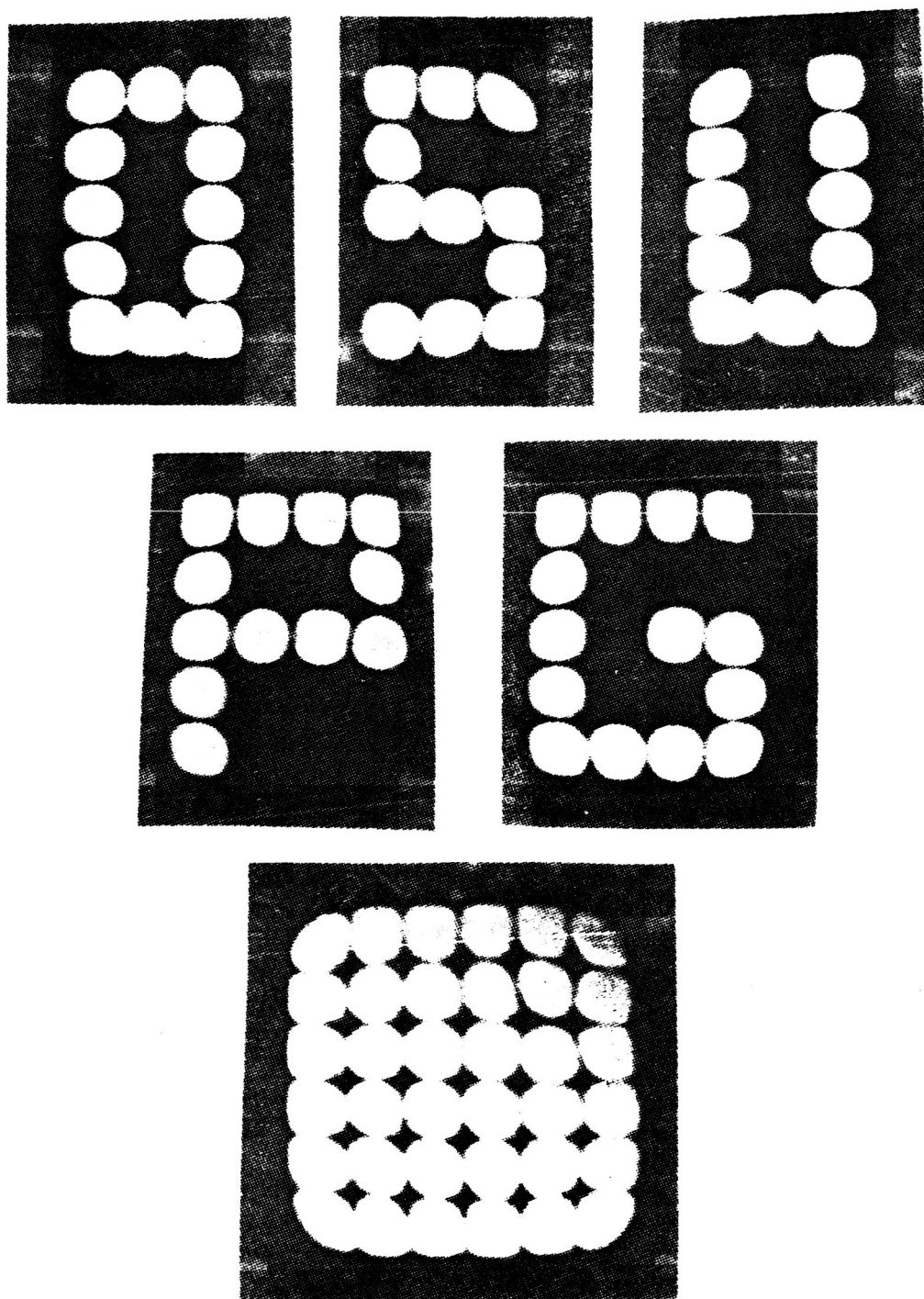


Fig. 16: Photographs showing various states of the optical flip-flop array.



valve. Another method, applicable to the present design, is to place an array of controllable polarizers in the plane of  $IIP_{LY}$ . If the array of polarizers corresponds to the array of flip-flops (which is imaged at  $IIP_{LY}$ ) then each flip-flop could be individually cleared merely by changing the polarization of the appropriate polarizer. This works because the light is linearly polarized at that point in the feedback loop. Other methods are sure to exist as well.

As a result of these experiments it was observed that the time to set a flip-flop depended upon at least two factors: Input beam intensity and operating point on the light valve response curve. The time to set a flip-flop varied from under one second to over eight seconds. The greater the intensity of the Input beam, the shorter was the time required to set a flip-flop. This relation was observed qualitatively but was not quantified. Changing the operating point, by changing the voltage, was observed to change the time required to set a flip-flop from less than one second to over eight seconds for a given Input beam intensity. Ultimately, of course, the setting time is limited by the relaxation rise time of the light valve.

It was further observed that the operating point on the light valve response curve varied from flip-flop to flip-flop. The difference in operating points could be seen by the speed with which a flip-flop would change states. This was confirmed by the fact that as the voltage applied to the light valve was changed, some flip-flops would lose their intensity bistability before others.

This difference in operating points is primarily due to the spatial nonuniformity of the light valve response. A variance in the loop

attenuation or in the intensity of the Read beam would also cause a variance in the operating points but this was not observed. (The Read beam was not uniform across its entire area of illumination, but across the small area utilized for the feedback of one bundle of fibers it was uniform.) To test the spatial uniformity of the light valve response, the output intensity was observed while the voltage was changed with no input illumination. A very obvious nonuniformity of response was seen. Some areas became quite bright while others were still dim. This nonuniformity was apparent even over an area as small as the 3mm square occupied by the image of one bundle of fibers.

This difference in operating points prevented complete stability from being attained for all combinations of flip-flops within the six by six array. For any given flip-flop there was a 0.4 VAC range in the light valve voltage over which intensity bistability could be attained. The center of this range averaged 7.9 VAC. The higher the voltage was in this range, the more susceptible the flip-flop was to being set by the noise generated by its closest neighbors (i.e. the tolerance on the SNR became tighter). The lower the voltage was in this range, the longer it took to set the flip-flop. For complete immunity to the cross-coupling noise of its neighbors, this range had to be tightened to 0.2 VAC. Thus, for the array of flip-flops to be completely stable for any configuration of bright and dim states, the center of the stable operating voltage range for all thirty-six fibers must lie within 0.1 VAC of one value (the value to which the light valve voltage will be set). Unfortunately, due to the spatial nonuniformity of the light valve response, this did not occur. For the photographs shown in Figure

16 the light valve voltage was set so that that particular configuration was stable. The voltage had to be changed with the configurations.

This problem can be surmounted (without replacing the light valve) either by increasing the intensity of the Read beam or decreasing the area being used on the light valve. If the Read beam intensity is increased, then the peaks of the light valve response curve shown in Figure 15 will be higher while the feedback load line will remain constant. This will result in a wider range of voltages over which bistable operation will occur, thus reducing the sensitivity to fluctuations in the light valve response due to changes in position. If the area being used on the light valve is decreased through decreasing the image guide to light valve magnification, then the variation in the light valve response over the image will be less because this variation is a function of distance. But, since the system was already pushing the resolution of the light valve (750 line-pairs per inch), decreasing the size of the image in order to decrease the area being used was not a viable option. The second solution is to increase the intensity of the Read beam.

As a result, the system was implemented successfully for only a four by four matrix of optical flip-flops. But it was implemented successfully thus verifying the design for an image guide-based optical flip-flop array presented in this report. In addition, the importance of fiber array mismatch and spatial nonuniformity of the light valve response was demonstrated.

#### D. CHARACTERISTICS OF THE IMAGE GUIDE

In this optical flip-flop array the image guide has been utilized as an array of independent optical data channels, as opposed to the more common usage as an image conduit. From this use, several important characteristics of the image guide became apparent, both advantages and disadvantages for such use. In this section these characteristics and their advantages and disadvantages will be discussed. As part of this discussion, the importance of the core/cladding ratio will be covered.

The most important characteristic of the image guide is its ability to operate as an array of independent optical channels. The output of each fiber is essentially independent of the output of any other fiber within the image guide. The presence of an evanescent field in the cladding prevents total independence but the image guide can be designed so that this effect is minimal. The ability to achieve independent flip-flops using the image guide is proof of this independence.

Another important characteristic of the image guide is flexibility. Rigid image guides have their uses but a flexible image guide is more versatile. Not only can the distance between the input and output planes be adjusted to meet the requirements of the system, but the orientation between the input and output can also be changed. Both of these properties were utilized in this design. The latter one was critical for the alignment of the system.

A major disadvantage of the image guide used in this system was the mismatch between the input and output fiber arrays. This limited the system to just one bundle of fibers. Such a mismatch is not unexpected. Galileo Electro-Optics Corporation and A.O. Reichart, both manufacturers

of image guides, quoted a mismatch tolerance of one mil (which corresponds to the width of two fibers) [19,20]. Manufacturing techniques are not developed to the stage where arrays can be matched within the width of the cladding between the fibers (0.025 mils).

A minor disadvantage of image guides is the need for a more elaborate imaging and alignment procedure when an image guide is added to a system. This need was discussed in Chapter II, Section D, Subsection 2. Designing such a procedure for this system was not too difficult of a task.

There are conflicting requirements for the core/cladding ratio of an image guide, depending upon whether the image guide is to be used as a data channel array or as an image conduit. Although an image guide can be used for either, it is best suited for one use or the other on the basis of its core/cladding ratio.

If an image guide is used as an image conduit, a large core/cladding ratio is desired. When used as an image conduit, it is important that as much of the light in the original image as possible be transported by the image guide. Any light that falls upon the cladding at the input is lost. In addition, several fibers are used to resolve each spot of the image so the independence of the fiber outputs is not critical in future imaging. Thus, a large core/cladding ratio is desired.

When used as a data channel, however, a large core/cladding ratio is not desired. The important factor now is that the fiber outputs be kept independent in future imaging. The relation of this to the core/cladding ratio can be seen in terms of the alignment tolerance and in terms of the space bandwidth product.

The smaller the core/cladding ratio, the greater is the alignment tolerance. It was shown in Chapter II, Section G, Subsection 2 that the alignment tolerance was dependent upon the width of the cladding between the fibers. If this is increased while the core size is kept constant, then the alignment tolerance will increase and the core/cladding ratio will decrease. It can be seen from this that a large core/cladding ratio is not as desirable. This can be further quantified by considering the space-bandwidth product.

The smaller the core/cladding ratio, the smaller the space-bandwidth product for the image of IGo. Designate the width of the fiber core by 'd' and the width of the cladding between two fibers by 's'. Then, for an image guide with N fibers, we can approximate the area of the image guide output by  $A = N(d+s)^2$ . The spatial bandwidth needed to resolve the image of IGo so that the fiber outputs remain independent is  $\kappa = a/(2s)$  for some constant 'a'. The value of 'a' is dependent upon the allowable cross-coupling SNR (experimentally, 'a' appeared to be unity). The dependence upon the cladding width is because this is what separates the edge of one fiber from another. (A resolution of  $1/(2s)$  is the minimum needed to resolve the fibers as distinct elements.) With these symbols the space-bandwidth product for IGo (as defined in Chapter II, Section E) is given by  $SW = N(d+s)^2 a^2 / (2s)^2$ . The information density ratio (defined in Chapter II, Section E) is proportional to the space-bandwidth product. It equals  $(2s/a/(d+s))^2 = 4/(a(r+1))^2$  where 'r' is the core/cladding ratio. It can be seen that for an information density of unity, which can be considered optimum in terms of informa-

tion sent (number of image elements) for given system bandwidth, the core/cladding ratio must be equal to  $(2/a)-1$ . (If 'a' is unity, then 'r' is unity). Therefore, the optimum core/cladding ratio (in this sense) is on the order of unity, not as large as possible.

#### E. SUMMARY

In this chapter the results of the implementation and operation of the optical flip-flop array design were given. It was determined that the alignment procedure was effective in accurately aligning the system. The fiber array mismatch between the input and the output of the image guide was found to be limiting, but the spatial nonuniformity of the light valve response proved to be the ultimate limiting factor, limiting the system operation to only a four by four array of flip-flops. Photographs showing the operation of the optical flip-flop array are contained in Figures 14 and 16. Finally, some of the characteristics of the image guide were discussed in terms of their advantages and disadvantages for use as a data channel array. The fact that a core/cladding ratio near unity was desirable, as opposed to the large core/cladding ratios desired for image conduits, was derived.

## CHAPTER V

### SUMMARY AND CONCLUSION

#### A. INTRODUCTION

The objectives of this report were to successfully create an optical flip-flop array using a liquid crystal light valve and an image guide in a feedback loop and to determine the useful characteristics and inherent problems associated with the image guide for such an application. The contents of Chapters II, III, and IV have served to satisfy these objectives. In the following three sections the contents of these chapters will be summarized, the important results reiterated, and future areas for research discussed. This will occur in Sections B, C, and D respectively.

#### B. SUMMARY

The main body of this report begins by presenting in Chapter II the theories relevant to the design and operation of the image guide-based optical flip-flop array. These fall into five categories. First the operation of the light valve is explained along with its response under feedback and the resulting stable states. The existence of these stable intensities is the heart of this design. Then, the operation of an image guide is discussed. Following this, a single lens system is analyzed in terms of the effect upon lens position and magnification when the object and image planes are moved an equal distance away from



the lens. The results of this are used in aligning the system. Next, the concept of a space-bandwidth product for an image is discussed and its usefulness in characterizing an image is explained. Finally, the resolution of two imaging systems (a lens and the light valve) are defined and the appropriate formulas given.

In Chapter III the apparatus used to create the optical flip-flop array is presented and its operation explained. This is handled in three sections. First, the operation of the individual components and their interactions are covered. Then, the operation of the these components as an optical flip-flop array is explained. Finally, the imaging and alignment of this system is discussed and a detailed procedure presented.

In Chapter IV the results of implementing this system are presented. These results fall into three categories. First, the results of the system initialization (achieving alignment and intensity bistability) are given. These verify the theoretical analysis done in Chapter III and point out the problem of fiber array mismatch between the input and output arrays of the image guide. Next, the results of operating this system are given. These demonstrate that an array of optical flip-flops can be constructed in this manner, but that the size of the array is limited by the spatial nonuniformity of the light valve response. Finally, the characteristics of the image guide are discussed in terms of their advantages or disadvantages for use in this type of role within an optical computing system. The desirable core/cladding ratio is analyzed in terms of whether the image guide is operating as an optical data channel array (as in this system) or as an image conduit.

In short, the operation of this image guide-based optical flip-flop array is analyzed both theoretically and in terms of the results when it was implemented. And, the image guide is discussed in terms of its useful characteristics and inherent problems for use in an optical computer.

### C. CONCLUSIONS

The significant conclusions of this report are summarized below:

1. The design shown in Figure 5 for an image guide-based optical flip-flop array works. This was demonstrated by the photographs in Figures 14 and 16. Due to the spatial nonuniformity of the response of the light valve, however, the implemented system was limited to a four by four array of flip-flops in general.

2. The image guide was able to be used successfully as an optical data channel array within this system. Several important conclusions about its characteristics came about as a result of this use:

- a. The fiber array mismatch between the input and output arrays of the image guide is a critical parameter. If it is too large then coupling one-to-one from the output into the input is not possible through simple imaging. Current manufacturing tolerances are not tight enough to permit this over a large area of the image guide.

- b. The presence of the image guide necessitates a special alignment procedure. This is due to the quantized nature of the image transmitted by the image guide which does not allow small adjustments in the input to be translated into equally small adjustments in the output.

c. A flexible image guide is more versatile than a rigid image guide. It provides more degrees of freedom for adjusting the system.

d. The core/cladding ratio for an image guide used as an optical data channel array should be close to unity. This is in contrast to the large core/cladding ratio desired for image guides which are used as image conduits.

3. The alignment procedure developed in this report worked quite well. Slide film proved to be a reliable record of the necessary image and the alignment components were able to compensate for all misalignments introduced by the feedback loop (with the exception of the fiber array mismatch).

#### D. AREAS FOR FURTHER RESEARCH

In the course of completing this report there have been several offshoots, improvements, or problems identified which merit further work. In this section some of these ideas will be presented.

The spatial nonuniformity of the response of the light valve was responsible for the ultimate limit on the size of the flip-flop array. Work needs to be done both in quantifying the nonuniformity and in improving it. Repeating the experiments with a more uniform light valve would yield better results.

The fiber array mismatch is also an important limiting factor in the size of the flip-flop array. There is much research to be done in

minimizing this mismatch. Such a minimization will not only increase the amount of the image guide which can be used as a data channel array in this feedback loop, but it will decrease the distortion and increase the resolution of image guides used as image conduits.

One method to increase the number of elements in the flip-flop array, without changing the nonuniformity of the light valve's response, is to decrease the core/cladding ratio to approximately one. This will enable the image of the fibers at the light valve to be smaller since the space-bandwidth product will be less, thus allowing more flip-flops to be created using the same area of the light valve.

The effect of the fiber array mismatch can be minimized with current technology by utilizing one bundle of fibers per data channel instead of one fiber. In this case it would be desirable to have the core/cladding ratio as large as possible in order to maximize the transmission of incident light. But the ratio of the bundle diameter to the cladding width between the bundles should be approximately one. This will again minimize the space-bandwidth product. (There is no need to resolve the individual fibers.)

One way to eliminate the effect of the fiber array mismatch entirely is to design an optical re-routing system which will map the output of one image guide onto the input of another, fiber to fiber. This might be done with a hologram. Not only would such a system be useful for this optical flip-flop array, but it would also enable two similar image guides to be connected without loss of resolution, something that can not be done currently. This latter application could be very useful.

Finally, taking this optical flip-flop array and using it to create a binary optical read/write memory is a project with great potential. A parallel-accessed optical RAM would be quite useful in an optical computer which depended upon its parallel nature to attain its results. Such an application would not be too difficult.

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